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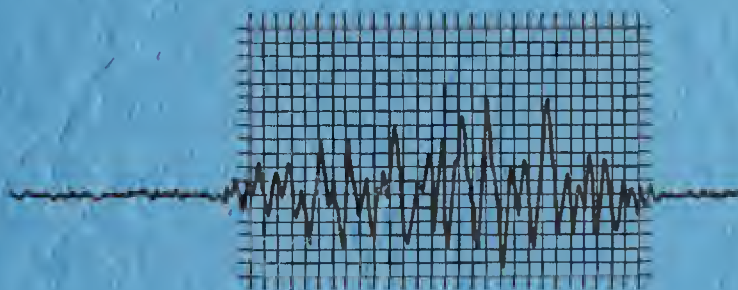
THE SEISMIC MOTION OF THE DEEP OCEAN FLOOR

D.D. PRENTISS and J.I. EWING



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COLUMBIA UNIVERSITY
PALISADES, NEW YORK

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GEOPHYSICS RESEARCH DIRECTORY
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UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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Lamont Geological Observatory
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THE SEISMIC MOTION OF THE DEEP OCEAN FLOOR

by

D. D. Prentiss and J. I. Ewing

ABSTRACT

Results of the first measurements of ambient seismic noise of the deep ocean floor below 2000 fathoms are presented. The measurements were made with vertical component seismometers at nine locations. At five stations in the Atlantic Ocean, amplitudes observed at 1 cps were 100 millimicrons at one site, 35 millimicrons at two sites, and less than 1 millimicron at the other two sites. At a station in the Gulf of Mexico, amplitudes of 35 millimicrons at 1 cps were observed. Amplitudes of about 1 millimicron at 1 cps were observed at three sites in the Arctic Ocean.

Amplitudes and periods remained essentially constant during the two days that data were recorded in the Gulf of Mexico and showed no correlation with nearby local meteorological storm activity. During the three days that data were recorded at the noisiest Atlantic site, rising and falling winds and seas over a broad area were weakly reflected as small changes in the amplitude of the ocean bottom noise. Similar small amplitude variations were recorded at Bermuda, 150 nautical miles to the northeast, but the absolute Bermuda amplitudes were an order of magnitude less than those at the noisiest Atlantic site.

Measurements in samples of up to one hour in duration were made in the Arctic Ocean at three stations. The measurements were

made at intervals during a 16-day period, and a good correlation was found in both time and amplitude between seismic noise on the ice surface and on the ocean bottom in the band from 1 to 10 cps.

A P wave train from a distant earthquake was recorded at the noisiest Atlantic site with a signal to noise ratio of about 3:1; this was the same signal to noise ratio seen nearby at Bermuda with a seismograph of similar response. In the Arctic, P waves from an Alaskan shock and a possible PKP phase from a New Zealand shock were recorded. The maximum P wave signal to noise ratio recorded in the Arctic for the Alaskan shock was 250:1. After a correction is made for the difference in epicentral distance, the signal to noise ratio at Ogdensburg, New Jersey, for this shock is only 20:1. Ogdensburg is quieter than an average station.

INTRODUCTION

For the first time, data have been obtained on the seismic noise of the deep ocean bottom. All measurements were made at sites far from continental margins and in water at least 1500 fathoms deep, and so are representative of the deep ocean basins. A large variation in the background noise at different sites was observed, one station being noisier than a noisy continental site and two others quieter than a quiet continental site. Unfortunately, data at present are so limited that the reasons for these variations are not immediately apparent.

The ability to measure the seismic motion of the deep ocean floor opens a large number of exciting new possibilities for research. Seismic station locations need no longer be limited to a small fraction of the earth's surface that is free of water. Valuable new data may be obtained on seismicity, earth structure, microseisms, wave propagation, etc. Instruments operating continuously at sites such as the very quiet ones discussed here will be extremely sensitive detectors of small distant seismic events if signal to noise ratios remain as favorable as the ones observed. There are many advantages in the use of such instruments in explosion seismology as well.

Figures 1 and 2 show the locations of the stations discussed. Stations 1, 2, 4, 5, and 9 were in the Atlantic Ocean, station 3 was in the Gulf of Mexico, and stations 6 to 8 were in the Arctic Ocean. Additional data pertaining to the stations are given in Table I which also includes similar data on all other ocean bottom seismic measurements for which the information is published. There are, of course, variations in certain parameters from station to station. At three of the Lamont stations seismic refraction profiles were conducted. The data from these refraction shots provide a rough calibration of the instruments under operating conditions; and the fact that the refracted wave signal-to-noise ratios were comparable to the signal-to-noise ratios seen with standard hydrophones provides strong assurance that the instruments were operating properly, at least in the frequency range of the refracted waves.

TABLE I

Source	Method	Date	Location	Nearest Continental Border in Naut. Miles	Water Depths in Fathoms	Type of Bottom	Semiconsolidated Sediment Thickness	Seismometer Free Period	Ambient Noise at 1 sec	Seismic Events Recorded	S/N	Hours of Data
LGO 1	TELE	10/10/59	35°55.5'N 68°37.5'W	360 590	2400 2500	mud mud	2 km	1/2 sec	<1 $m\mu$	-	-	2-3
LGO 2	TELE	17/9/60 20/9/60	30°17.5'N 65°55.5'W	-	-	-	1 km	1/2 sec	120 $m\mu$	Q. m 6¼ (Pas)	3:1	72
LGO 3	TELE	26/1/61 28/1/61	24°00.0'N 91°27.5'W	170	1800	mud	4 km	1 sec	35 $m\mu$	-	-	48
SEDOV 1	TR	22/6/61	54°43'N 19°52'E	<50	14	?	?	3 sec	?	-	-	?
SEDOV 2	TR	23/6/61	54°43'N 19°52'E	<50	14	?	?	3 sec	?	-	-	?
SEDOV 3	TR	15/7/61	55°22'N 16°43'E	<50	25	?	?	3 sec	?	-	-	?
SEDOV 4	TR	18/7/61	58°00'N 9°45'E	<50	55	?	?	3 sec	?	-	-	?
SEDOV 5	TR	27/7/61	34°52'N 16°25'W	420	1125	mud?	?	3 sec	?	-	-	?
SEDOV 6	TR	9/8/61	28°04'N 44°10'W	1080	1250	mud?	0	3 sec	<100 $m\mu$	-	-	?
LGO 4	TELE	10/12/61	25°52.5'N 68°35.5'W	700	2400	mud	1 km	1/2 sec	<1 $m\mu$	-	-	1/4
TI 76	TR	8/3/62	Off Catalina Isl.	<50	700	mud	?	1 sec	?	-	-	?
TI 77	TR	8/3/62	Off Catalina Isl.	<50	700	mud	?	1 sec	?	-	-	?
TI 78	TR	15/3/62	" "	<50	660	mud	?	1 sec	13 $m\mu$	UNE	5:1	?
TI 81	TR	26/3/62	" "	<50	660	mud	?	1 sec	?	-	-	?
TI 82	TR	27/3/62	" "	<50	660	mud	?	1 sec	?	-	-	?
TI 83	TR	28/3/62	" "	<50	660	mud	?	1 sec	13 $m\mu$	UNE	4:1	?
TI 88	TR	5/4/62	" "	<50	31	sand	?	1 sec	13 $m\mu$	UNE	5:1	?
TI 89	TR	6/4/62	" "	<50	24	sand	?	1 sec	?	UNE	-	?
SIO 1	TR	4/ 62	San Diego Trough	<100	1300	mud?	?	1 sec	5,000 $m\mu$	-	-	?
SIO 2	TR	4/ 62		<100	1300	mud?	?	1 sec	70 $m\mu$	-	-	?
LGO 5	FR	6/4/62	31°38.3'N 64°21.5'W	700	2400	mud	1/2 km	1 sec	35 $m\mu$	-	-	12
LGO 6	TELE	1/5/62	80°48.9'N 172°51'E	150	1400	mud	2½km	1/2 sec	1 $m\mu$	-	-	1-1/3
LGO 7	TELE	10/5/62	80°51.3'N 172°51'E	150	1400	mud	2½km	1/2 sec	1 $m\mu$	Q M 5(Pal)	250:1	1
LGO 8	TELE	17/5/62	81°04.5'N 172°10'E	150	1400	mud	2½km	1/2 sec	2 $m\mu$	-	-	1/3
LGO 9	FR	27/9/62 28/9/62	31°36.3'N 64°44.5'W	700	2400	mud	1/2 km	1 sec	35 $m\mu$	-	-	24

Table I Explanation

Source: LGO 2 reads Lamont Geological Observatory Station 2. SEDOV was the ship used to gather the data reported in Monakov (1962). TI stations are reported in Texas Instruments Semi-Annual Technical Report No. 3 (1962). SIO results are from Scripps Institution of Oceanography Final Technical Report, "Ocean Bottom Seismic Measurements" (1962).

Method: TELE refers to the acoustic telemetry of data to the surface; FR refers to film recording of data on bottom; TR refers to magnetic tape recording of data on bottom.

Semiconsolidated Sediment Thickness: Semiconsolidated refers to compressional wave velocities of less than 4.0 km/sec. These thicknesses are average values representative of the immediate area around the station taken from the best available refraction and reflection profiles. Where refraction profiles were shot to the bottom seismograph, the thickness is measured directly under the instrument.

Ambient Noise: All amplitudes (zero to peak) are displacements in $m\mu$ (10^{-6}mm). To permit direct comparison with LGO data, data at 1 cps were taken from the power density spectra of TI and SIO and were converted to displacement. Such derived values may not be strictly comparable due to differences in data reduction techniques but the errors should not be serious.

Seismic Events Recorded: Q refers to natural earthquakes. M refers to earthquake magnitudes measured from surface waves, and m to magnitudes measured from P waves. These quantities are related by $m = 2.5 + 0.63M$. UNE refers to underground nuclear explosion.

S/N: The signal to noise ratios listed were measured from broad band recordings using the maximum P phase amplitude and the average noise amplitudes present just before the P arrivals.

In the following, the instrumentation and methods of data handling and processing are discussed briefly. The data are then discussed, considering the four noisy sites together and the five quiet sites together. In addition to a description of the noise at each station, an attempt was made to correlate variations in the noise with meteorological effects. For the period range studied, such correlation appears weak at best. Where appropriate, signal to noise ratios for seismic waves from earthquake sources are given.

INSTRUMENTATION

Telemetry Technique. The instrumentation and the operating techniques for the first three stations are described in Ewing and Ewing (1961). Briefly, the instrument which goes to the ocean floor consists of a seismometer with a free period of 1/2 second plus associated electronics which amplify the seismometer output and frequency modulate a 12 kilocycle per second carrier. This carrier is transmitted acoustically to a ship maintaining position approximately over the unit. The ship receives the signal through the transducer of a standard echo sounder. The signal is then amplified, recorded with a lower carrier frequency on a tape recorder, and simultaneously recorded in demodulated form on a chart recorder. All the data except that from stations 5 and 9 were telemetered in this fashion. Data at these two stations were recorded on bottom using 35mm film, a sensitive galvanometer, and electronic amplification.

Emplacement Methods. For stations 1 through 3 the bottom unit was expendable and there was no mechanical link to the ship during recording. For stations 4-9 the operation was similar, except that the instruments remained coupled to the surface through a slack cable which permitted retrieval of the package but which did not contribute significantly to the background noise being measured. For station 4 the linkage included a 1500-pound weight at the end of a steel cable. Two hundred meters of manila line coupled this weight to the seismometer package which housed, in a single pressure case, the seismometer, electronics and battery power for six hours of operation. The pressure case was fitted into a large circular frame which assured that the instrument would be properly oriented on bottom. Vibrations during lowering caused a characteristic chirping at the receiver. The chirping stopped when the seismometer reached bottom. Shortly thereafter the impact of the weight was detected. Measurements were then obtained until the ship drifted far enough to drag on the weight. By slacking the wire at the proper rate, the seismometer was decoupled from the ship for as long as seven minutes. Since the instrument was capable of being reset, at station 4 five different noise samples were obtained. At stations 6 to 8 in the Arctic, a similar technique was used, except that the only weight used was the bottom seismograph, and a much lighter winch and cable were employed. After the instrument touched bottom, it was decoupled by piling some 100 to 200 meters of wire nearby on bottom. Decoupling was tested at the surface by plucking the cable vigorously. This

instrument remained quiet for periods as long as an hour. The ice at this time was drifting about one mile per day as compared with the ship's drift rate of 45 miles per day at station 4.

The film recording seismograph used at stations 5 and 9 was lowered and recovered with positive buoyancy polypropelene line which was buoyed at the surface and connected to a 500-pound weight on bottom. The seismograph was decoupled from the weight and buoy line with 600 feet of slack manila line. At stations 5 and 9, 12 and 24 hours of data were recorded, respectively.

Calibration Methods. Calibration of the instruments used at stations 1 and 2 is described in Ewing and Ewing (1961). The response of the electronic portion of the system was determined experimentally and the overall system response obtained by combining this information with the seismometer response curves supplied by the manufacturer. Calibration of the instruments at stations 3, 4, 6, 7 and 8 was done more directly using the impedance bridge technique described by Willmore (1959). A series of tests on different geophones showed that the sensitivities might deviate as much as 50% from those claimed by the manufacturer. Therefore, the calibrations of stations 1 and 2 are in doubt by this amount. The instruments used at stations 5 and 9 were calibrated through a separate set of coil windings. The electromotive constants of the coils were determined by weight lift tests; then the shape and magnitude of the response curve were determined in the laboratory using steady state signals.

Prior to placing the instruments on bottom at stations 5 and 9, test records were made at the seismological station in Bermuda. These compared well with the short period records made with the standard station seismographs.

Figure 3 shows the magnification curves for use with the records illustrated in Figures 4 and 5. A record and curve for station 5 is not included because the high amplitude and faintness of the signal on the film makes photographic reproduction impractical. Station 9 is not illustrated because the light spot was out of focus in these records.

Data Reduction. Two methods have been used to obtain the displacement spectra of Figures 6 and 7. In the first method, predominant periods and amplitudes are measured on broad band visible recordings of the telemetered, taped signal or on photo enlargements of the film recorded signals. A smooth line is then drawn through these data points. A second method, limited to use with the data on magnetic tapes, is to pass the signals from the tapes through a standard 1-octave band-pass filter and then to record the signals on a drum recorder. An envelope is drawn that includes 95% of the peak-to-peak amplitude for record lengths of from 3 to 5 minutes' duration. The pass band center frequency is changed and the same section of tape is passed through again. Because the filter insertion loss is 6 db, or a factor of 2, these amplitudes can be converted directly to zero-to-peak particle displacement using the appropriate magnification curves. The lower

level, long-period signals that are difficult to measure on unfiltered recordings are easily measured with this technique. The two methods have been carefully compared and found to give equivalent results.

There are, of course, sources of signal in the data that are not due to seismic events or to ambient bottom motion. Tape recorder wow and flutter and doppler shifts induced by receiving ship motion are two such unwanted signal sources on the F.M. tape recordings. Wherever possible the magnitude and character of these sources have been determined. Specific cases will be dealt with in the discussion of the individual stations.

DATA DESCRIPTION

Noisy Sites. At stations 2, 3, 4, and 9 the ambient seismic background was large compared with the background at an average continental station as defined by Brune and Oliver (1959). Figure 1 shows the locations of these stations and Figures 4 and 5 are short samples of the ambient signals recorded. The displacement spectra of these noisy sites are plotted in Figure 6 with the three Brune-Oliver curves for reference.

Station 2. This station in the Atlantic has the largest amplitudes of any of the noisy sites and the longest continuous record of ocean bottom microseisms. Signals were recorded from 17 to 20 September, 1960. The sample shown in Figure 4 is typical of the background which varied little in amplitude or character during the three days of recording at this site. Below

the record of station 2 in Figure 4 is a sample of a short-period vertical Benioff record made in Bermuda at the same time.

The displacement spectra of the ocean floor and Bermuda are shown for comparison in Figure 6. The long-period end of the station 2 spectrum is dashed because the size of the seismic signals at these periods is comparable to the effects caused by the wow in the tape recorder and by power fluctuations. The spectrum from 1 to 10 cps was obtained from high speed chart recordings, made aboard ship, which were free of possible flutter in the tapes. The Bermuda amplitudes were obtained using records from the short- and long-period station seismographs. Unfortunately, at this time no satisfactory explanation can be given for the large difference in the spectra between Bermuda and station 2.

For the first few hours of operation at station 2, the carrier frequency went through large, erratic excursions which finally died away. Subsequent shooting to the instrument demonstrated apparently normal operation in the 1-10 cps band but leaves the calibration in some doubt at lower frequencies.

Figure 8 shows a plot of the average record amplitude at the station and above it the average wind velocity over a 300-nautical mile radius about the station. Weather and sea conditions varied markedly over the station during the three days recorded. The seas went from state 2 through 5 (when for a time conditions were too rough to maintain contact with the bottom seismograph) and back to sea state 2 at the end of the three-day period. This storm is easily seen in the wind plot of both Bermuda and the ocean

bottom station but is only weakly reflected in the ambient seismic amplitudes at the two places. It would seem that the seismic background was somewhat insensitive to significant changes in wind and sea state over a broad area either at Bermuda or on the ocean bottom. A correlation of the periods of the microseisms and the ocean swell was also attempted as the demodulated signals were observed aboard the receiving ship, but no correlation was apparent.

The record samples in Figure 4 from Bermuda and station 2 also show the pP and PP phases of an earthquake, magnitude 6 (Richter) 25.2° distant from station 2 and with epicenter near the Panama-Columbia border. The first motion of the P wave on the ocean bottom was lost in a time break on the tape recordings. The signal to noise ratio for the P phases is about 3:1 for both locations even though the amplitude of the noise at station 2 was ten times that at Bermuda around the P phase frequency of 1 cps.

Station 3. This station located in the Gulf of Mexico showed amplitudes somewhat less than the maximum levels seen on land around 1 cps. Data were collected here for approximately two days during the interval from 26 to 28 January, 1961. Again, in Figure 6, the dashed portion of the spectrum indicates the influence of tape recorder wow. This spectrum stops at 1 cps because of the tape recorder flutter and the lack of reliable chart recordings. There was further trouble with this instrument characterized by occasional impulse-like shifts in the carrier frequency followed by a slow decay to the center frequency. Refraction shooting to the bottom seismograph gave the expected response, demonstrating reliable operation in the frequency range of 5 to 10 cps.

Figure 4 shows a sample of the background at the Gulf of Mexico site, as well as refracted and direct arrivals from a 9-pound charge at a range of 25 miles. The general character of the microseisms is not much different from those at station 2 and here, too, there was little variation in the background over the two days for which data were recorded. The wind and sea state over the instrument were mild (sea state 2) during these two days, but small meteorological storm centers within 200 miles had no detectable effect on the seismic background levels. No earthquakes were recorded at this station.

Station 5. This station, the first at which the film recorder was used, was located some 50 miles south of Bermuda. Data were gathered for 12 hours on 10 April, 1962.

The photographic record cannot be reproduced here because high gain and high background level produced a very faint trace on the film. It was possible, however, to read the record on a microfilm viewer, and the spectrum so obtained is shown in Figure 6. It coincides almost exactly with the spectrum for station 3 in the band from 1 to 2 seconds. The Bermuda background at this time was about one half of the ocean bottom values for the period range between 1 and 2 seconds. The sea was calm, about state 2. SOFAR ranging shots were fired and detected by the instrument. No earthquakes were recorded either on the ocean bottom or at Bermuda during this period.

Station 9. At this station, the second where film recording was used, 24 hours of data were recorded south of Bermuda near the location of station 5. Some difficulty was experienced with the focusing of the light spot and the record is not reproduced here. Figure 6 shows some selected amplitudes measured from the record.

Although the amplitudes measured here are comparable with those measured at other stations, there is serious doubt about the validity of the results because (1) the seismometer mass was not positioned properly, and at its operating temperature was riding very near the upper stop, and (2) subsequent examination showed a small metal filing lodged between the mass and the coil which may have caused improper response.

Quiet Sites. At stations 1, 4, 6, 7, and 8 the ambient seismic background was equal to or less than the background at a quiet continental site (Brune and Oliver, 1959). Figure 1 shows the locations of stations 1 and 4 while Figure 2 shows the positions of the Arctic stations 6 through 8. Figures 4 and 5 show sample records of the low background stations, and Figure 7 shows the particle displacement spectra of the Arctic stations, and limiting values for stations 1 and 4.

Station 1. Figure 4 shows the nearly flat trace of the background at this first station in the Atlantic about 300 nautical miles northwest of Bermuda. About three hours of data were gathered during 24 hours of operation. Data were lost because of difficulty in maintaining contact with the bottom unit.

The record includes two refracted ground arrivals and the direct wave from a 9-pound charge at a range of 15 miles demonstrating that the unit was functioning normally. The record was made at relatively low gain so that the direct arrival and the later reflections would not be lost.

Figure 7 shows a representative system noise curve converted to particle displacement for this station. As there was no indication of malfunction of the bottom unit and a good refraction profile was obtained with it, the ambient seismic background for station 1 must lie somewhere below this noise curve. No earthquakes were recorded at this site.

Station 4. Figure 4 shows one of the five short samples of data obtained at station 4, 450 nautical miles southwest of Bermuda. This record was made at a much higher magnification than that illustrated for station 1. The regular long period waves of 4 to 6 seconds period are due to doppler modulation of the F.M. carrier frequency by the vertical motion of the receiving ship. The amplitude of the frequency deviation of the waves shown was from 4 to 6 cycles which is quite close to the doppler effect calculated from the observed sea swell of about 6 seconds period and zero-to-peak amplitude of 3 feet (sea state 2). Superimposed on the long-period doppler is a small, regular 1½ cps motion which looks artificial. These waves are possibly the result of cable vibration. The very large amplitude signals on the rest of the record are caused by the instrument hanging on the cable, by the touchdown of the 1500-pound weight and by the cable noise (CN)

induced by an insufficient rate of cable slacking.

After eliminating the effects of doppler modulation and the possible cable vibration, we again conclude that the seismic background of station 4 must lie somewhere below the system noise of the transmitter and receiver, shown in Figure 7. No earthquakes were recorded during the 15 minutes of data gathering time.

Stations 6 through 8. The Arctic stations 6 through 8 will be discussed together because all the measurements were made with the same instrument and the same technique in roughly the same region. Figure 2 shows the location of these stations. The platform from which these measurements were made was ARLIS II, a drifting ice island supported by the Arctic Research Laboratory, Point Barrow, Alaska.

Figure 5 shows samples of the noise recorded at these three sites. As most of the seismic background lies in the band between 1 and 10 cps, records made at these recording speeds and magnifications show little of the character of the ambient background. The scale was selected to be consistent with the other illustrations and to show the P wave train to advantage in the illustration for station 7. Records of higher gain and speed were used for the analyses of the results shown in Figure 7.

These displacement spectra were obtained from three lowerings between 1 and 17 May, 1962, during which about 2½ hours of data were recorded. Amplitudes measured on the ocean bottom and on the ice were about 1 millimicron at 1 cps, comparable to a quiet continental station.

The variation in the amplitude of the bottom seismic noise shows some correlation with changes in the ice drift velocity and in the wind velocity over the ice island for these data samples. The seismic background noise of the ice surface varies in the same manner and has, except for certain details, the same displacement spectrum. Tentatively, it appears that the ice layer, water and bottom sediments are coupled together and must be considered as parts of an acoustic system.

This coupling of seismic energy between water surface and sea floor is probably characteristic of all the oceans. The absence of large amplitude gravity waves on the Arctic Ocean's surface (Hunkins, 1959) provides unique conditions under which seismic measurements can be made that demonstrate the coupling.

The illustration for station 7 in Figure 5 shows the P wave train from a magnitude 5 (Pal) earthquake near Mt. McKinley, Alaska, about 22.5° distant. The bursts of noise labeled RN are caused by radio interference. The radio transmission stopped shortly after the arrival of the first motion labeled P. Picking the exact time of arrival of P through the radio interference was accomplished by listening to the carrier modulations as the record was written from the tape. The trace just below the RN is the background about 15 minutes after the arrival of P and is representative of the seismic background without radio interference. The high frequencies (above 2 cps) for this recording were cut to minimize the radio interference. In Figure 3 the effect of this high frequency cut-off has been included in the magnification curve.

At this quiet Arctic station there is an excellent signal to noise ratio of 250:1 for the maximum amplitude waves arriving 15 to 20 seconds after the first motion P. This P phase was also clearly recorded at Palisades, New York (a somewhat noisier than average station at 1 second), and at Ogdensburg, New Jersey (a station with less than average noise at 1 second) After correcting the P wave amplitudes for the added $25\frac{1}{2}°$ of distance from the epicenter, the signal to noise at Palisades was 12:1, and at the quieter Ogdensburg station it was 20:1. A distance correction of 2 was derived by assuming that all factors at the stations were alike but distance and that Gutenberg and Richter's tables of P wave attenuation with distance as used in magnitude calculations apply. The superior Arctic signal to noise ratio is mainly a consequence of the low seismic background. Thirty minutes after this event another smaller signal arrived at the right time to be a PKP phase from a New Zealand earthquake, but high cable noise makes positive identification difficult.

With the low seismic background at these Arctic stations, earthquake P waves should be frequently detected. Under these conditions it would be instructive to compute the expected frequency of occurrence. From the S/N of the $M = 5$ shock, one can extrapolate to a minimum detectable magnitude of $m = 3.7$. M measured from surface waves is related to m measured from P waves by: $m = 2.5 + 0.63M$. Then from the observations, $m = 5.7$ and $S/N = 250$, a $S/N = 2.5$ would be expected from a $m = 3.7$ shock at the same distance and azimuth. Gutenberg and Richter's formulas

from the"Seismicity of the Earth" predict a frequency of about 0.8 shocks per hour if all shallow earthquakes in Alaska, Japan, Mexico and Central America above m = 3.7 are detected. A rate of about 2.7 shocks per hour is predicted for the whole world. However, small shocks at long distances would not be detected. For the distances and azimuths considered above, one would not expect to see more than one or two earthquakes during the 2½ hours of satisfactory recording.

Conclusions

Large differences in the amplitude of ambient seismic noise of the ocean bottom have been measured at different times and places. During one period of high activity, body waves from a distant earthquake were clearly recorded, as well as the higher frequency waves from explosion sources. The signal to noise ratio for the earthquake body phases was at least equal to the S/N for the same shock recorded nearby on the island of Bermuda. The S/N of another P phase recorded in the Arctic was 12 times the S/N of an average continental station. The Arctic Ocean S/N was approximately equivalent to that which would have been observed at a quiet continental site. Thus it appears that the S/N ratios for body waves on at least some parts of the ocean floor will be as good as those at average and quiet land stations.

The measurements in the Arctic Ocean, made during the spring season, indicated very low background noise levels. Furthermore, the ice surface during the same period was found to be as quiet as the ocean bottom and the operation of instruments on the

ice surface may prove to be the most effective way of detecting seismic events in this area. As the ice surface is more accessible, instrumentation and recording techniques can be made more comparable to those at land stations. Although the present data are limited to the spring season, the results certainly seem to warrant study during the rest of the year.

From this limited data, particularly with regard to time, no final conclusions can be drawn on the origin or mode of propagation of ambient seismic energy on the ocean floor. Nevertheless, the conservation of signal to noise ratios, which has been observed, suggests that the absolute amplitude of the ambient noise may be as much a function of local geology, bottom structure and location in the ocean basin as it is of meteorological conditions at the surface. In fact at the one station in the Atlantic, where measurements were made over a long enough time for meteorological conditions to change, only a weak correlation could be made of the variations in surface sea conditions and bottom noise. Monakov (1962) has been able to show some dependence of period and amplitude of the ambient microseisms on the geologic structure of the bottom in agreement with our conclusions.

Summary

We find that the S/N ratios for earthquake body waves on the ocean floor are comparable to land stations. The Arctic Ocean bottom and surface were observed to be as quiet as the quietest land stations in measurements confined to the spring season. The absolute amplitude of the ambient noise at a location may be more

dependent on local bottom structure and elastic parameters than on sea conditions at the surface, but much longer samples of bottom noise data are needed to resolve this questions.

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Figure Captions

Fig. 1 Mercator projection showing the positions of stations 1-5 and 9. The 300-nautical-mile circle about station 2 is the area over which wind velocities were averaged from synoptic weather maps and plotted in Figure 8.

Fig. 2 Polar projection showing the positions of Arctic stations 6-8 in inset map. Large scale locator map shows positions of bottom contours and continental borders.

Fig. 3 Magnification curves for sample records of ocean bottom noise in Figures 4 and 5.

Fig. 4 Samples of ocean bottom ambient seismic noise. The vertical arrows represent the particle displacement in microns at 1 second. Station 1: G and D are refracted and direct arrivals from a 9-lb charge at a range of 15 miles. Station 2: pP and PP are body phases from a magnitude 6 (Pas) shock 25.2° distant. P was lost in the minute break; this is an unfiltered recording. Bermuda: a tracing of a short period Benioff microfilm record showing the same earthquake. Station 3: late G and D arrivals from a 9-lb. charge at a distance of 25 miles. The much weaker first G is lost in high ambient background not present in station 1. Station 4: the high amplitudes on the left are the 'chirps' produced by ship motion as the instrument hangs at the end of the cable. The second burst of chirps is probably

Fig. 4 (cont'd) touchdown of the 1500-lb. weight and CN are small cable jerks. Bandpass filtered from 0.08 to 4 cycles per second.

All records, with the exception of the Bermuda tracing, were made on GeoTech Helicorders from tape recordings.

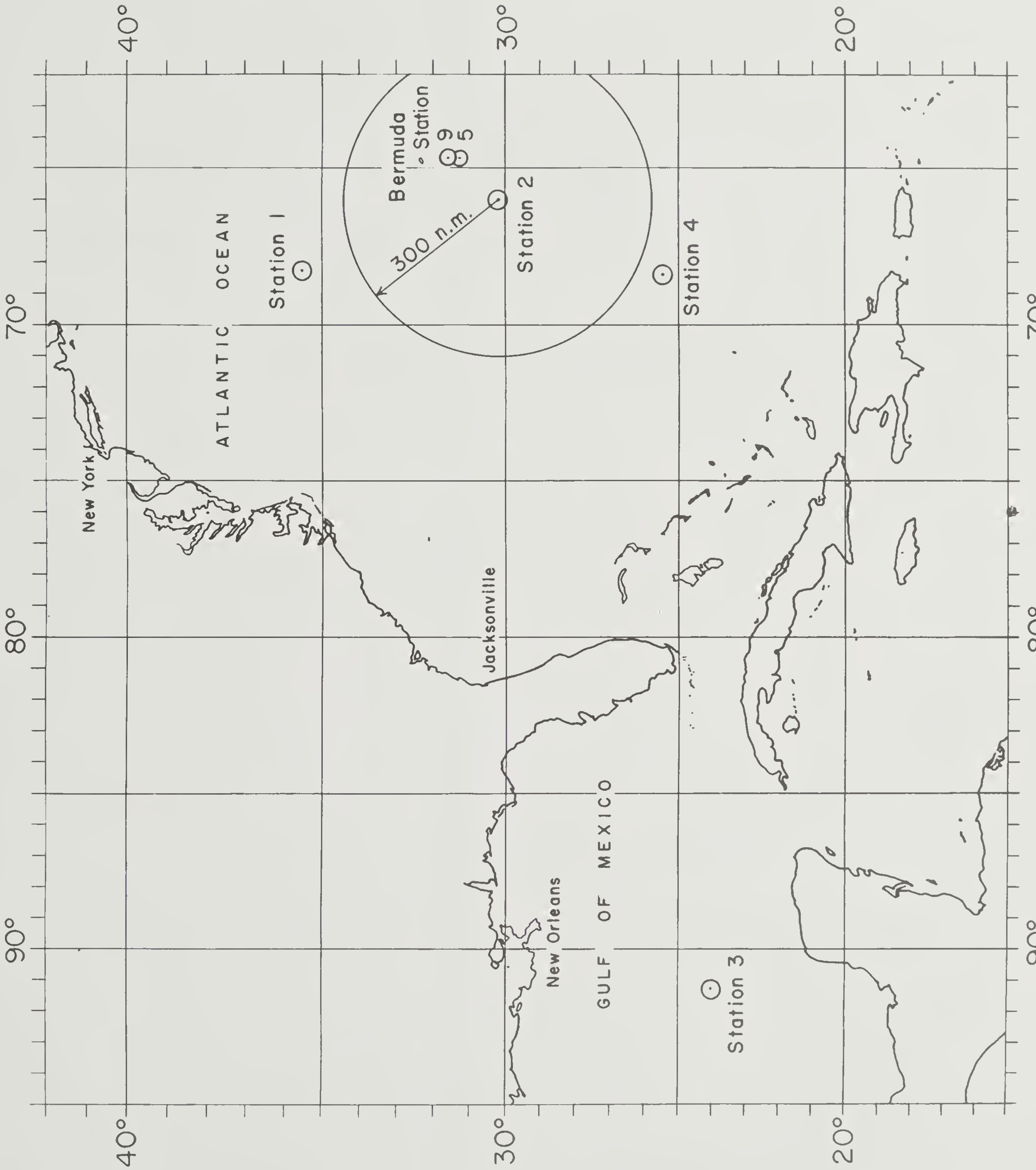
Fig. 5 Samples of ocean bottom seismic noise. The vertical arrows represent the particle displacement in millimicrons at 1 second. Station 6: the transient signal each minute is caused by the bandpass filter ringing from time breaks on the magnetic tape; recording bandpassed from .02-10cps. Station 7: RN is noise caused by radio interference on the tape recordings. P is the first motion of an M5 (Pal) earthquake 22.5° distant near Mt. McKinley, Alaska. Recording bandpassed from .08-2 cps. Station 8: CN is cable noise.

Fig. 6 Spectra of particle displacement per octave bandwidth for stations 2,3,5 and selected amplitudes for station 9. The dashed portions of the curves are the less reliable parts. The Bermuda spectrum was obtained using both the long- and short- period seismographs with the area of overlap dashed. The three dotted curves labled "Max", "Ave", and "Min" refer to the seismic background levels present on land, and are taken from Brune and

Fig. 6 (cont'd) Oliver (1959).

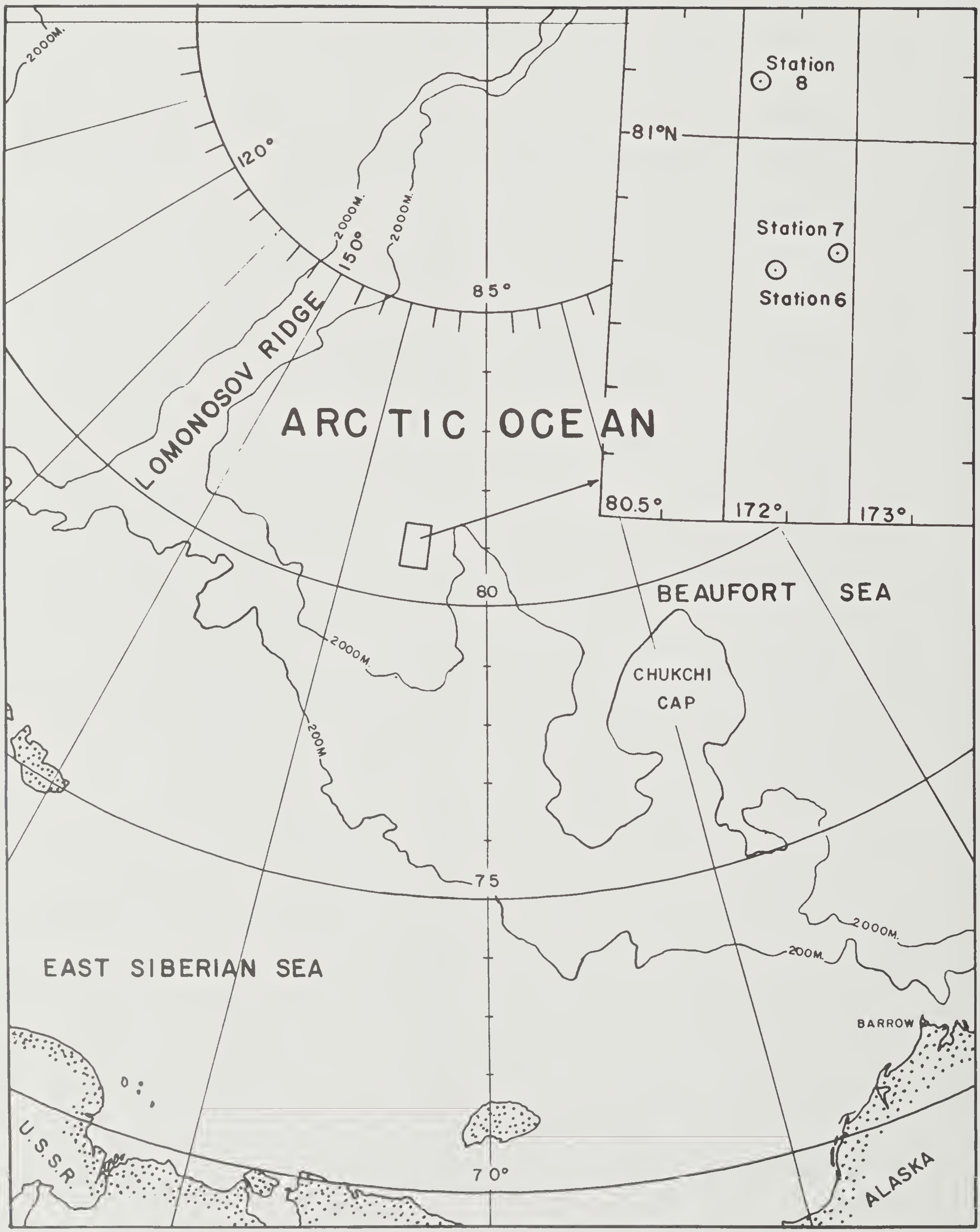
Fig. 7 Spectra of particle displacement per octave bandwidth for station 6-8 and the system noise levels for 6-8 and 1 and 4. Broken curves are the data obtained in the Arctic. The dotted curves are from Brune and Oliver (1959). showing average and minimum levels for continental locations.

Fig. 8 Wind velocity and trace amplitude versus time for station 2 and Bermuda. Wind velocities, taken from synoptic weather maps, were averaged over an area 300 nautical miles in radius centered on station 2, and the Bermuda wind was taken from the same maps. The envelope of the peak-to-peak trace amplitudes were measured at approximately 6-hour intervals.



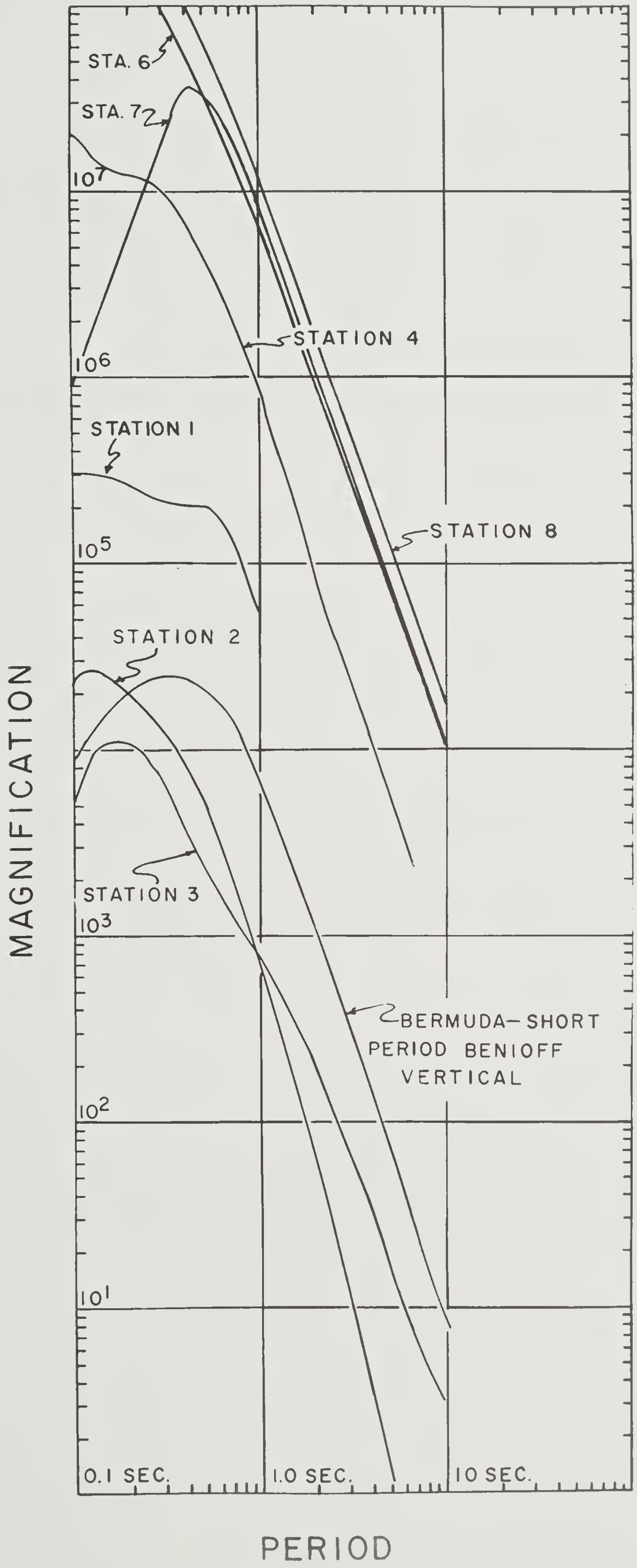
40°
30°
20°
70°
80°
90°
ATLANTIC OCEAN
Station 1
Station 2
Station 4
Station 3
300 n.m.
Bermuda
Station
9
5
New York
Jacksonville
New Orleans
GULF OF MEXICO

Figure 1.



ARCTIC OCEAN
LOMONOSOV RIDGE
BEAUFORT SEA
CHUKCHI CAP
EAST SIBERIAN SEA
U.S.S.R.
ALASKA
BARROW
Station 8
Station 7
Station 6
81°N
80.5°
172°
173°
120°
150°
85°
80
75
70°
2000M.
200M.

Figure 2.



STA. 6
STA. 7
10^7
10^6
STATION 4
STATION 1
STATION 8
10^5
STATION 2
STATION 3
10^3
BERMUDA–SHORT PERIOD BENIOFF VERTICAL
10^2
10^1
0.1 SEC.
1.0 SEC.
10 SEC.
MAGNIFICATION
PERIOD

Figure 3.

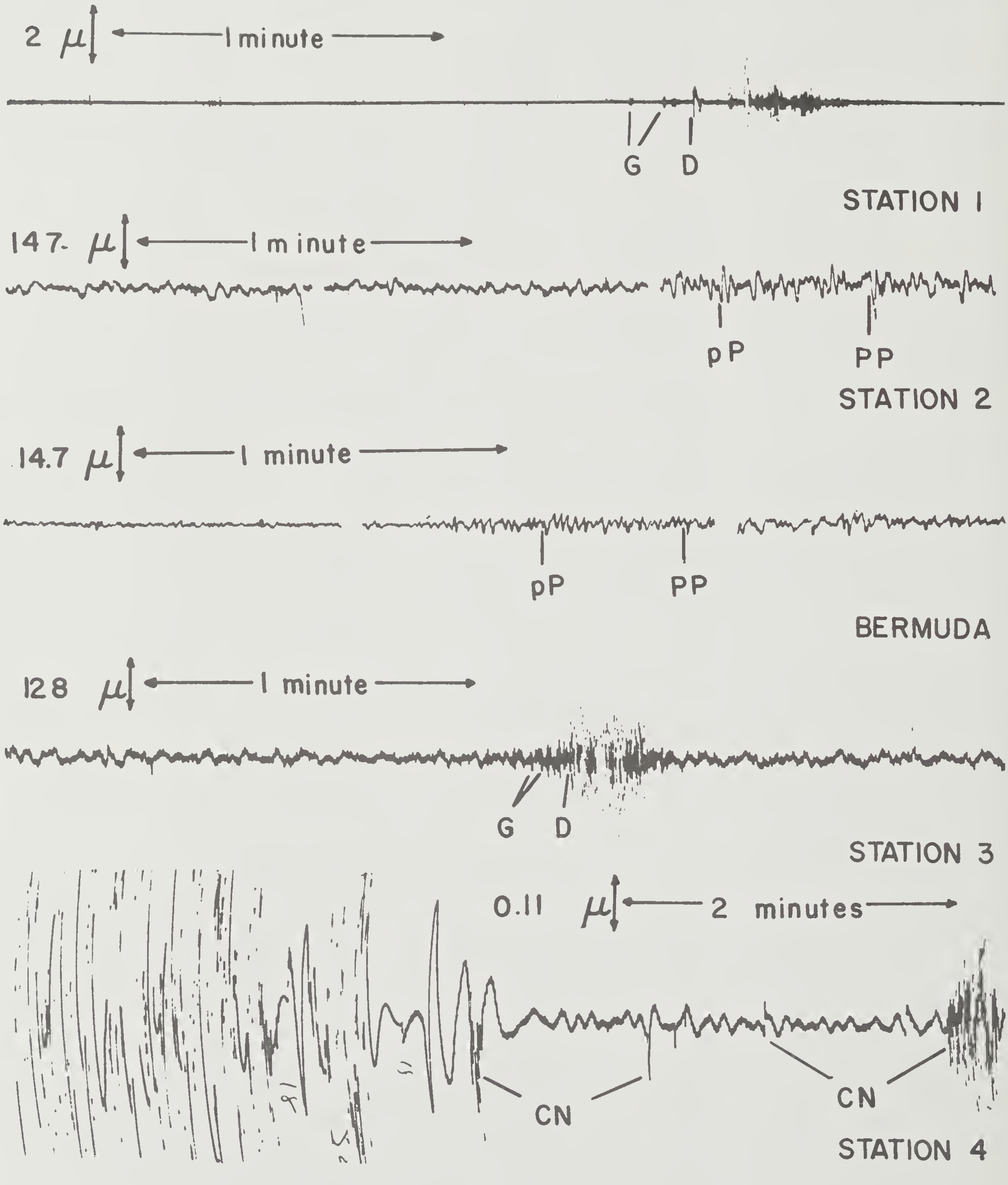

2 μ
1 minute
G
D
STATION 1
147 μ
1 minute
pP
PP
STATION 2
14.7 μ
1 minute
pP
PP
BERMUDA
128 μ
1 minute
G
D
STATION 3
0.11 μ
2 minutes
CN
CN
STATION 4

Figure 4.

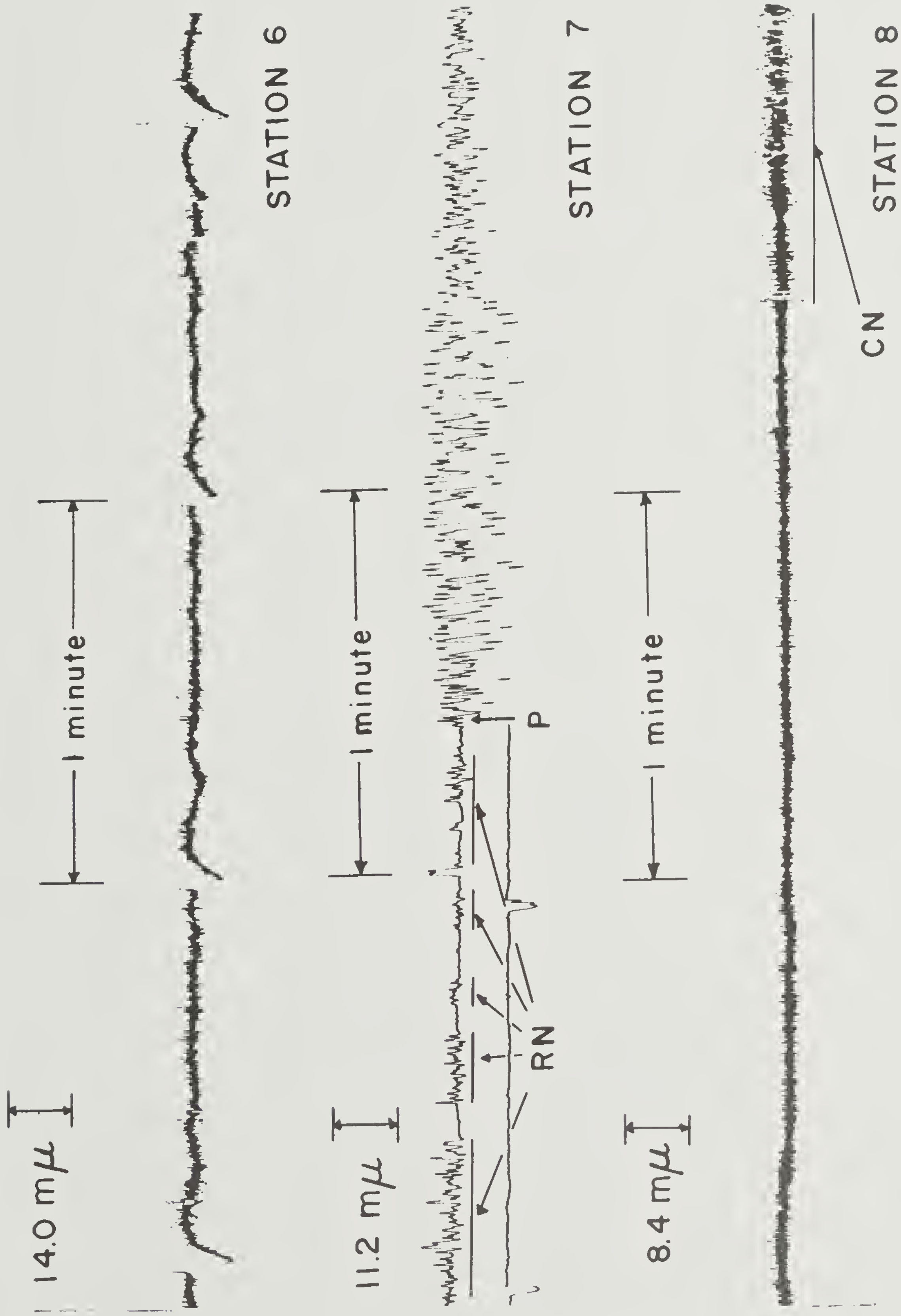
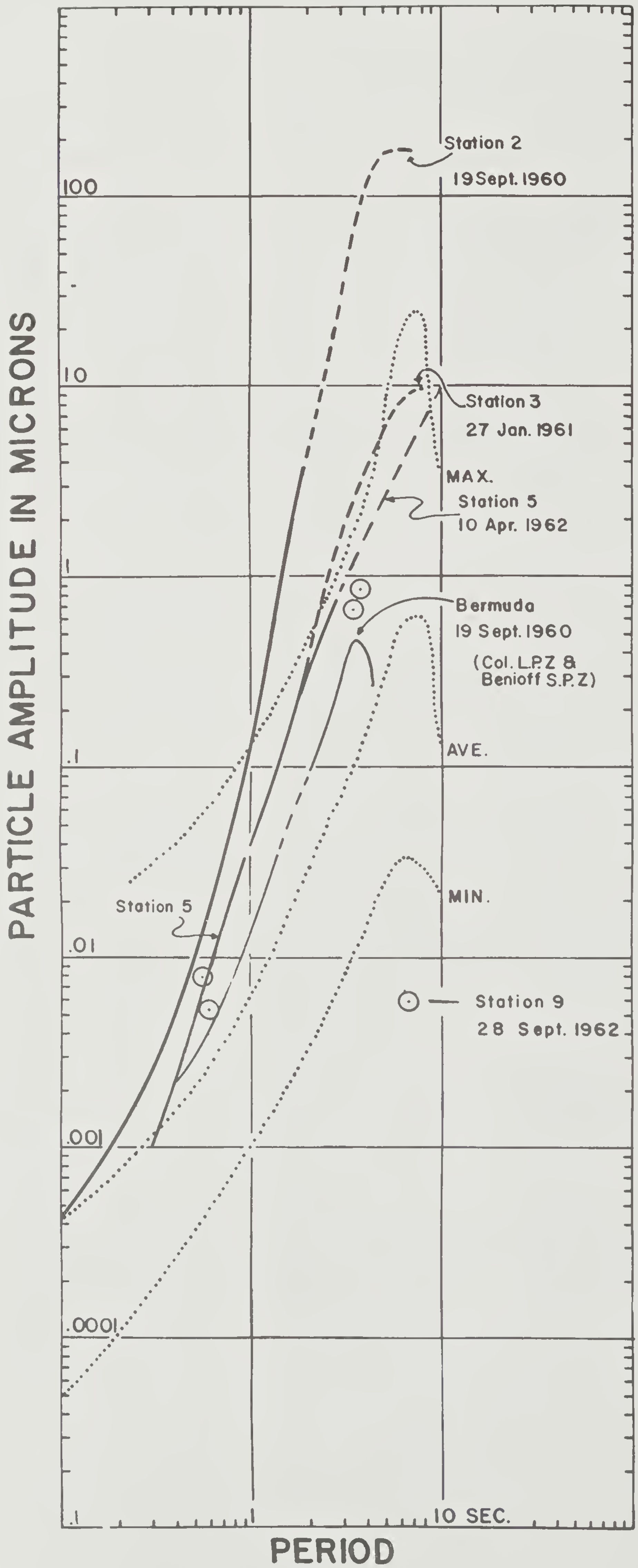

14.0 mμ
1 minute
STATION 6
11.2 mμ
1 minute
P
RN
STATION 7
8.4 mμ
1 minute
STATION 8
CN

Figure 5.



Station 2
19 Sept. 1960
Station 3
27 Jan. 1961
MAX.
Station 5
10 Apr. 1962
Bermuda
19 Sept. 1960
(Col. L.P.Z &
Benioff S.P.Z)
AVE.
MIN.
Station 5
Station 9
28 Sept. 1962
100
10
1
.1
.01
.001
.0001
.1
1
10 SEC.
PARTICLE AMPLITUDE IN MICRONS
PERIOD

Figure 6.

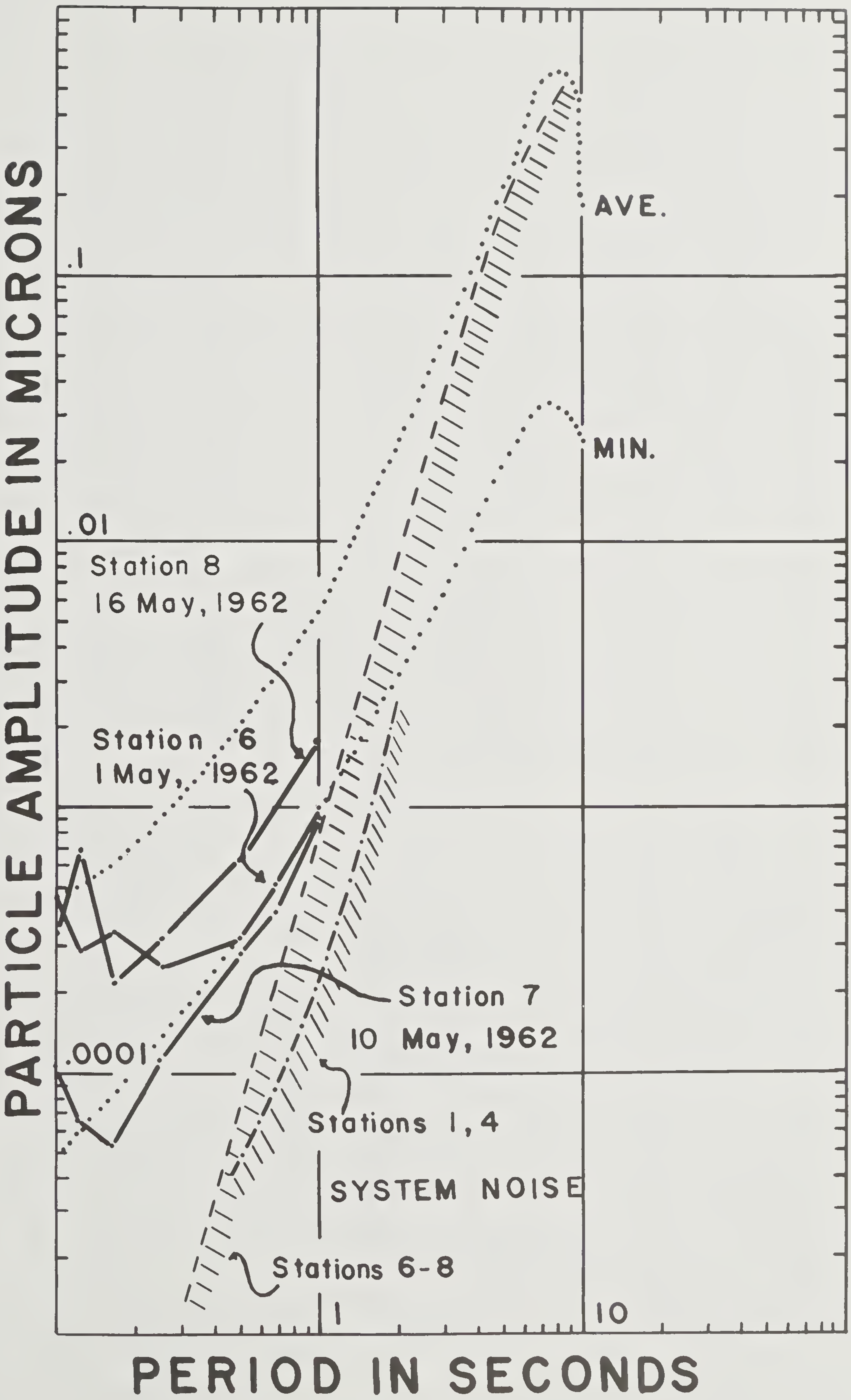
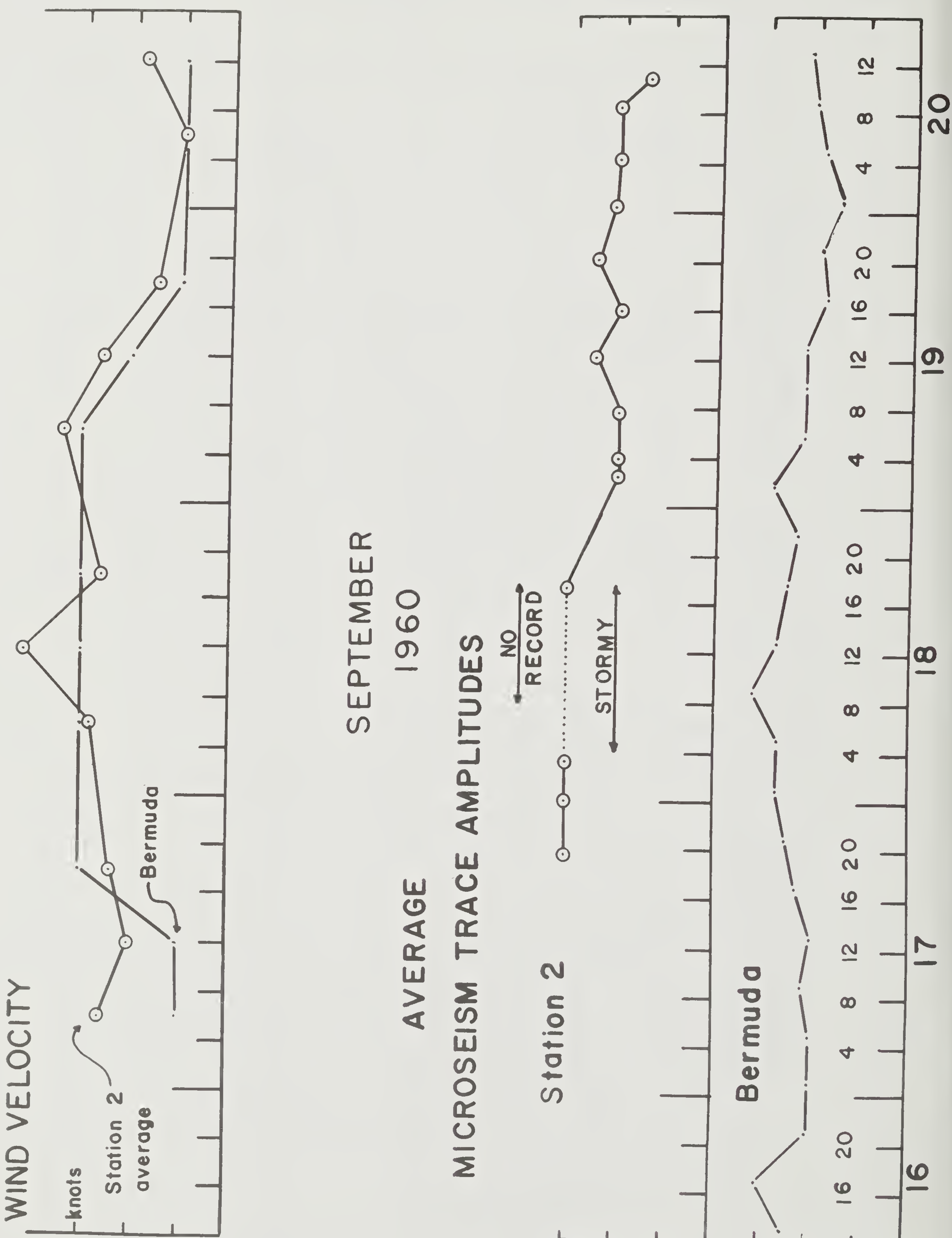

PARTICLE AMPLITUDE IN MICRONS
.1
.01
.0001
AVE.
MIN.
Station 8
16 May, 1962
Station 6
1 May, 1962
Station 7
10 May, 1962
Stations 1, 4
SYSTEM NOISE
Stations 6-8
1
10
PERIOD IN SECONDS

Figure 7.



WIND VELOCITY
knots
15
10
5
Station 2 average
Bermuda
SEPTEMBER
1960
AVERAGE
MICROSEISM TRACE AMPLITUDES
NO RECORD
STORMY
Station 2
Bermuda
3mm
2
1
16
17
18
19
20

Figure 8.

APPENDIX I

Introduction

The following is a complete technical report on the telemetering technique used for most of the stations discussed in the preceding pages. The telemetering units designated MK 1 through 3 correspond to the instruments used at stations 1 through 3. The transmitters and receivers used at stations 4, 6, 7, and 8 did not differ fundamentally from the first three units. Consequently, detailed descriptions of their circuits have not been included.

THE FOLLOWING TECHNICAL REPORT NO. 5

CONTRACT NObsr 85077

COVERS WORK UNDERTAKEN FOR THE BUREAU OF SHIPS, U. S. NAVY, UNDER CONTRACT NObsr 85077 AND IS INCLUDED WITH THIS REPORT WITH THE PERMISSION OF THE BUREAU OF SHIPS.

LAMONT GEOLOGICAL OBSERVATORY
Columbia University
Palisades, New York

TELEMETERING SEISMOGRAPHS FOR OCEAN BOTTOM OBSERVATIONS

by

D. E. Koelsch, A. C. Hubbard, and B. Luskin

Technical Report No. 5
CU-5-62-85077 Geology

January 1962

CONTENTS

ILLUSTRATIONS

A. Introduction

Since 1938 several different methods of obtaining deep ocean seismic records have been used (Ewing and Vine, 1938). This report deals with an acoustic telemetering ocean bottom seismograph program which was begun in 1959 at Lamont.

Measurements of seismic background noise on the deep ocean floor are nearly non-existent. The data from microseisms on the ocean floor can shed new light on the generation and propagation of microseisms. The effect of the continental margin on earthquake surface waves can be studied. A more complete understanding of average ocean crustal structure can be obtained from shocks propagated along pure ocean paths (Ewing and Press, 1952). Marine refraction profiles of much greater range and detail can be obtained. Finally, unusual seismic waves, such as the theoretically predicted but hitherto unobserved Stonely waves, might be detected.

B. GENERAL DESCRIPTION

The system consists of a seismograph on the ocean bottom, whose amplified signal controls an F. M. acoustic carrier of 12 kc (Fig. 1).

The receiver, aboard ship at the surface, uses a standard AN/UQN-1 echo sounding transducer to pick up the frequency modulated carrier. The received signal is amplified and recorded on magnetic tape for data reduction at a shore station. The signal is also demodulated and continuously monitored on a strip chart recorder.

C. BOTTOM UNIT DESCRIPTION

1. MK-1

The MK-1 unit built in 1959 used a standard 2-cycle vertical geophone with an intrinsic sensitivity of 5-volt/in/sec, and an output resistance of 4,000 ohms.

The transistorized amplifier sensitivity was 6 db down at 1.5 cycles/second.

The amplified seismic signal controls a variable inductor, the frequency-determining element in an F.M. oscillator. The F.M. oscillator signal is amplified to drive an acoustic transducer at a power level of 1 watt. The MK-1 unit was powered by an array of dry cells potted in roofing tar.

An 83 km seismic refraction profile was obtained with this unit (Ewing and Ewing, 1961). The low signal to noise ratio of the acoustic link interfered with the receiver demodulation to recover the seismic signal on shipboard.

Because of the low acoustic power, difficulty was experienced in keeping the listening ship over the bottom unit. Also, the low sensitivity of the geophone, amplifier and receiver did not allow recording of microseism background.

2. MK-2

The MK-2 utilized a specially constructed seismometer with an intrinsic sensitivity of 45 volt/in/sec, internal coil resistance of 200,000 ohms and a 2-c.p.s. natural frequency. To match this impedance and obtain a low amplifier noise level, electron tubes

were used to amplify the seismic signal. The pre-amp gain was 100, down 6 db at .1 and 1.4 second period. A 12 kc rejection filter was included in the pre-amp to eliminate any feedback from the transmitter output to the seismometer.

A 2 kc sharply tuned amplifier and envelope detector was included in the pre-amp to allow "pings" at this frequency to be sent from the listening ship, causing a carrier frequency shift at the bottom unit. Elapsed time from "ping" to reception of the carrier shift back at the receiving ship gave a means of obtaining the slant range to the bottom unit.

The 12 kc transducer used on the bottom unit had a mechanical Q of about 7, permitting frequency deviation of $\pm$ 1 kc while still providing adequate power output.

The amplifier and variable inductor gave an F.M. shift of 0.23 cps/microvolt input to the amplifier. The maximum permissible signal to remain within the 1 kc deviation limit is therefore 4 millivolts. For the MK-2 the minimum discernible signal was 0.3 microvolt. The limits of the minimum discernible signal and the maximum permissible provided a dynamic range in excess of 80 db.

One disadvantage of the variable inductor is that signals with very fast rise times cause core magnetization which may take several seconds to disappear. This magnetization affects the inductance in the same manner as an input signal and offsets the oscillator frequency.

The battery pack for the MK-2 contained 2 six-volt, 100 ampere-hour storage batteries in series, to power the transmitter output stage; an independent 12 volt, 60 ampere-hour storage battery to provide filament power for the tubes and power for the transistor circuits other than the output stage. These batteries were modified (Fig. 8) to be pressure compensated and waterproofed so that they could operate unprotected at the ambient pressure of the ocean bottom.

This was accomplished by fitting the electrolyte fill holes with 4-inch lucite plastic tubes and potting the top of the battery with Scotch-cast No. 212 Epoxy resin to cover and waterproof all exposed terminals.

Each cell was then filled brimful of electrolyte, and a flexible rubber finger-cott, full of distilled water, was tied over the end of the filling tube. This flexible reservoir allowed the transmission of hydrostatic pressure to the interior of the battery and provided for contraction of the electrolyte under pressure.

The increased power from this pack as compared to that of the MK-1, plus increased efficiency in the design of the transmitter output circuit, resulted in a much more secure acoustic link. This, plus a trainable receiving transducer (Fig. 9), simplified the task of keeping the listening ship on station.

The MK-2 was dropped about 150 miles southwest of Bermuda in September of 1960. Two seismic refraction profiles were obtained, one 268 km long, the other 52 km. During this time an earthquake on the Panama-Colombia border was recorded (Ewing and Ewing, 1961).

Microseism activity was very clearly recorded, indicating a level on the order of that shown as maximum for land stations (Brune and Oliver, 1959).

3. MK-3

The MK-3 resembled the MK-2 save for the extension of the low frequency response of the pre-amp, the gain dropping 6 db at 15 sec period, and the inclusion of a calibration bridge (Wilmore, 1959), to simulate a standard seismic input to the geophone. A multivibrator driving a relay applied a rectangular current pulse of 20 sec duration to the bridge every 15 minutes. In this fashion a check was possible on the entire system as responses changed due to weakening batteries.

Due to the extended low frequency response of the pre-amp, the minimum discernible signal was 3 microvolts, reducing the dynamic range to 60 db.

Figure 4 gives the F.M. transmitter response curves in terms of frequency shift for a unit seismic velocity of 1 micron per second, for both the MK-2 and the MK-3.

The MK-3 seismometer was modified by filling with silicone oil to provide mechanical damping of 0.4 critical. This contributed to improved low frequency response.

A MK-3 was dropped in the Gulf of Mexico in January, 1961. Two refraction profiles were obtained, one of 230 km, the other 172 km in length.

Microseism noise at this time was close to the maximum for land stations (Brune and Oliver, 1959).

D. MK-3 CIRCUIT

1. Pulser

The calibrate signal is generated by a free running asymmetric multivibrator, Q-1, Q-2, with an on time of 20 secs, off time of 15 minutes. The multivibrator drives a switching circuit, Q3, Q4, which operates a relay K-1. The relay applies a 135 millivolt pulse to the calibrate bridge. The battery B-1 is a miniature mercury cell, rated to last more than a year in this application.

2. Calibrate Bridge

The HS-10 seismometer is included at all times in a bridge circuit (Fig. 2, 5) R3, R4, R5, and R6 to allow system calibration (Wilmore, 1959) during operation. For seismic signals, the bridge merely acts as a high resistance shunt, which lowers seismometer sensitivity approximately 5%. Before the unit is lowered, the bridge is balanced with the seismometer clamped. With the seismometer unclamped, as in normal operation, the calibrate current flowing through the coil causes it to move. This coil motion will provide a constant seismic reference signal.

3. Pre-Amp

Signal is fed from the calibrate bridge to the grid of V-101-A (Fig. 6), type 5751, a ruggedized, high gain twin-triode. A 12 kc twin-T rejection filter, R-104, R-105, R-106, C-104, C-105, C-106, prevents 12 kc from the transmitting transducer from feeding back through the system. The seismic signal is further amplified by a second stage V-101B. Independent plate supply batteries, B-101, B-102, are used for the pre-amp stages.

The signal from V-101B passes through a low pass filter (R-111, R-112, C-110, C-111), cutting frequencies above 150 cps. This filter passes seismic signals, but prevents feedback of 2 kc ripple from the 2 kc envelope detector to the input of the 2 kc amplifier.

Any 2 kc signals for ranging purposes are selected by the 2 kc sharp-tuned filter, L-101, L-102, C-113, C-114, C-115, and amplified by V-102A a second 5751 tube. Output from this stage is rectified to reproduce the envelope shape of the 2 kc signal. This envelope signal and the seismic signal are fed to V-102B, a cathode follower. This stage matches the control circuit of VL-101, a variable inductor. The control winding resistance is 440 ohms. Its inductance of 7 henrys gives an upper frequency limit of 10 cps.

4. FM Oscillator

VL-101 (Fig. 7), the variable inductor, provides a simple method of frequency modulating an oscillator. VL-101 and C-201 form the frequency determining circuit of a cross-coupled oscillator, Q-201, Q-202, with a center frequency of 12 kc.

C-201 contains both ceramic and paper capacitors in ratio 1:10 to reduce carrier drift due to changing temperature.

A Zener diode, CR-201, is employed to stabilize the collector supply voltage of the oscillator and to reduce carrier drift due to weakening supply batteries.

5. Driver Stage (Fig. 7)

Transformer T-201 matches the output impedance of the oscillator to the input impedance of a push-pull driver stage, Q-203, Q-204. This stage provides the power gain necessary to drive the output stage. The driver section is operated class C for good efficiency. C-204 increases efficiency by reducing harmonics of the carrier frequency.

6. Output Stage

T-202 is a U.T.C. transformer type A-20. The connections used are not mentioned by the manufacturer, but give an impedance ratio of 125 ohms half primary to 17 ohms for each secondary circuit.

This gives proper matching from the driver to the output stage. The output transistors, Q-205, Q-206, are type 2N174, mounted on the end cap of the pressure vessel to provide good thermal contact with the ocean water, which at average depths is within a few degrees of freezing.

The output stage drives a magnetostrictive transducer mechanically resonant at 12 kc, with a mechanical Q of about 7.

A separate battery, B-12, is provided for this stage alone. The drain from this battery, 2.5 amp at 12 volts, is more than 4 times as great as that from the other 12 volt supply, B-11. Frequency variations in the carrier cause variations in the supply current, due to the frequency dependence of the transducer impedance. This current fluctuation causes corresponding supply voltage changes which would cause instability if coupled into the rest of the circuits. Thus an independent supply is necessary.

C-205 tunes the transducer. The output stage is operated class C and for an input power of 30 watts, delivers 22 watts of electrical power to the transducer.

E. DROP METHODS

1. MK-1

Two MK-1 units were built, a Mod-1 and a Mod-2. The electronics of each unit were the same; however, the methods of getting the units on the bottom differed.

The MK-1, Mod-1 (Fig. 14) had the electronics pressure case and the battery pack housed in a thin wall metal cylinder. A three-foot metal spike was affixed to the bottom of the unit. This spike dug into the sediment, keeping the unit upright. The geophone was in a separate pressure case which had a cartwheel base. It was hung on the end of a trigger arm and when the geophone reached the bottom, it allowed the arm to raise, releasing the battery unit from the lowering cable and giving it a few feet of free fall to imbed the spike firmly into the sediment.

The MK-1, Mod-2 (Fig. 15) had the electronics and battery pack mounted on the top of a thirty-foot steel core pipe with the geophone in a pressure case on the bottom of the pipe. The core pipe was attached to the thousand-pound core head by a shear pin. When the trigger weight reached the bottom, it allowed the trigger arm to raise, releasing the unit when the nose was fifteen feet above the bottom. The resulting velocity imbedded the geophone well down into the sediments, giving good seismic coupling. When tension was put on the

cable, the weak link sheared, leaving the seismograph in the bottom, and allowed for retrieval of the core head and trigger mechanism.

2. MK-2

This unit (Fig. 16) was designed to fall freely from the surface ship to the ocean bottom. The package was shaped roughly like a rocket, with tail fins and spin tabs to assure vertical descent. The nose carried a 6-ft-long, 2½-in. diameter pipe which penetrated the bottom sediment and maintained the unit upright after it came to a stop. The body of the unit, about 18 inches in diameter and 8 feet long, housed the battery pack and the pressure vessel for the seismometer and electronics. The 12 kc transducer was mounted on the tail.

3. MK-3

The MK-3 was designed for a "soft" landing on the end of a cable. It could be recovered if it did not function properly upon reaching bottom. After a successful checkout, the cable was released by a messenger and trigger mechanism. The seismometer and its pressure case were gravity leveled for tilts up to 30° by suspension from a universal joint.

F. RECEIVER

1. Pre-Amp

The receiving transducer was a standard Navy AN/UQN-1B echo sounding type in a trainable mount. (Fig. 9)

The 12 kc carrier (Fig. 10) was fed to an input transformer T-301 and then to two stagger-tuned pentode amplifier stages. The bandwidth was broadened by lowering circuit Q through resistors R-302

and R-305 across Z-301 and Z-302, respectively. This broadened response curve is shown in Figure 11. The B+ supply for each stage is decoupled and regulated.

2. Mixer

The amplified 12 kc carrier is mixed in V-401 with a 13 kc signal to obtain a 1 kc difference frequency. A low pass, two section, Pi filter, C-405, L-401, C-404, L-402, passes only the difference frequency, removing components of the carrier and 13 kc signals.

3. I.F. Amplifier

V-402A is a 12 AT7 high mu triode serving three functions: (1) monitor speaker amplifier, (2) output stage to the frequency meter, (3) output stage to the tape recorder.

4. F.M. Discriminator

This is a commercial frequency meter, made by Hewlett Packard, which recovers the seismic signal from the frequency moedulated I.F. signal by feeding its "pulse" output through a low pass filter, C-411, L-403, C-412, with high cutoff of 10 cycles per second. The seismic information is amplified by V-402B and then sent to a Sanborn D.C. amplifier and pen recorder. The 1 kc I.F. frequency is recorded on magnetic tape for later processing.

G. SUMMARY AND CONCLUSION

Excellent results from past seismograph drops indicate the great usefulness for the telemetering ocean bottom seismograph, especially in the following areas:

1. Significantly longer refraction profiles are made possible because of: lower ambient noise level at the ocean floor compared with a hydrophone at the surface; removal of at least one water path; and the removal of the coupling loss through the last interface.

2. The resolution of refraction profiles would be increased to facilitate the study of thin sedimentary layers because the surface-to bottom and bottom-to-surface paths are eliminated.

3. The earthquake recorded by the MK-2 unit indicates that telemetering bottom seismographs may have better signal-to-noise ratio in certain period ranges than average land base stations (Ewing and Ewing, 1961).

4. The placing of existing seismograph stations has been limited to land base stations. With the ocean bottom telemetering seismograph, it is possible to place stations on the ocean floor. This would improve the distribution and allow placing of stations at points of particular interest.

5. The telemetering bottom seismograph has provided data on ocean bottom microseism level which, before this program, had been unobtainable.

Future models for earthquake studies should have a three-component seismometer system, two horizontal, one vertical, with a frequency response to periods of 15 seconds. This system could include a notch filter centered at 6 seconds period which would compensate for the shape of the microseism noise spectrum (Brune and Oliver, 1959).

The equipment should have the capability of discerning a millimicron of ground motion in the 1-sec to 15-sec period range. A fourth short period vertical seismometer with a frequency range from 1 to 10 cps and minimum discernible ground motion of .1 millimicrons should also be incorporated.

A free fall device has succeeded once; however, in the present state of the art, it would be preferable to lower the unit to the bottom, check for proper operation, and then free the seismograph using a core trip mechanism. The complete system cannot be tested just before lowering because the accelerations aboard ship are sufficient to cause the preamplifier to overload even if the seismometer is clamped.

The systems which appear most promising are the following: A free fall device which would hit the bottom, driving the seismometer into the ocean floor ten to twenty feet. The unit should have a long term battery supply such as an atomic-thermocouple generator or a fuel cell. It should have a memory unit which would store information for at least a month and telemeter it to the surface on command at an

accelerated rate. Taking into account power requirements and physical size for the memory unit and peripheral equipment, the most applicable device to date is a tape recorder with information stored in a digital code.

A ship would go out to the area once a month, command the bottom unit to send the stored data to the surface via the acoustical telemetering link, make a tape recording of the received signal, decode the signal and make a seismogram. This method has the major disadvantage of delaying the interpretation of the data.

Another method would be to place a unit well out from shore on an underwater cable. This would have the advantage of obtaining the record immediately and may solve the battery problem by using the same cable to supply the power. The cable system offers much greater simplicity because the data would not have to be stored at the unit. The disadvantages of this system include the cost of obtaining and laying the cable which would limit the distance from the shore station to the drop site.

It may be desirable to develop not only a large long-term system for earthquake and microseism studies but also to develop a simple expendable model for seismic refraction and reflection shooting.

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G. B. Tirey, J. F. Hennion, S. M. Gerber, D. D. Prentiss, and Dr. J. L. Worzel made major contributions throughout the course of the project.

S. Thanos was responsible for the design of the asymmetric multivibrator in the calibration circuit.

Occasional participants in this work were A. Stockel, R. Zaunere, P. Kunsman and F. S. Wendt.

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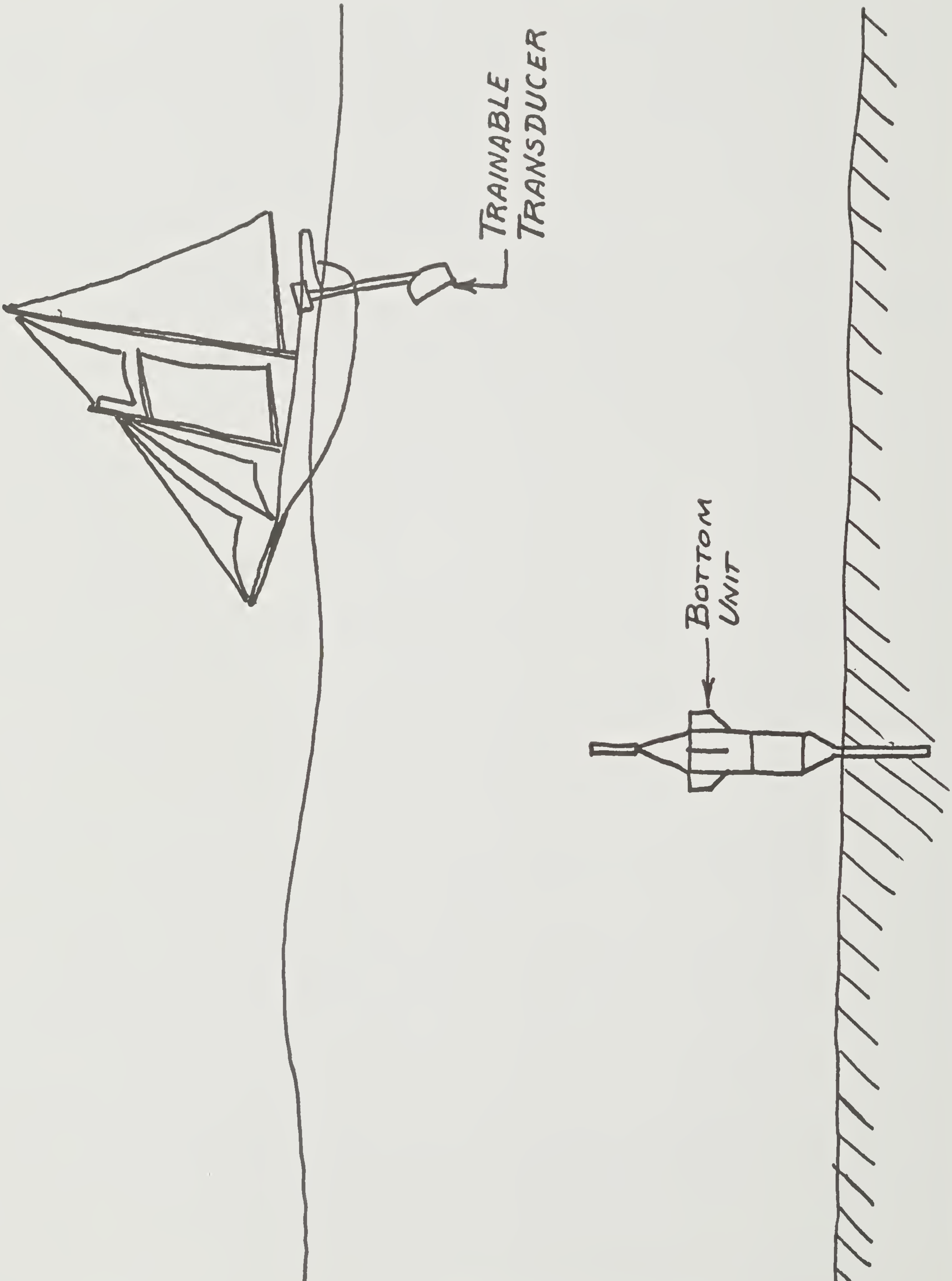
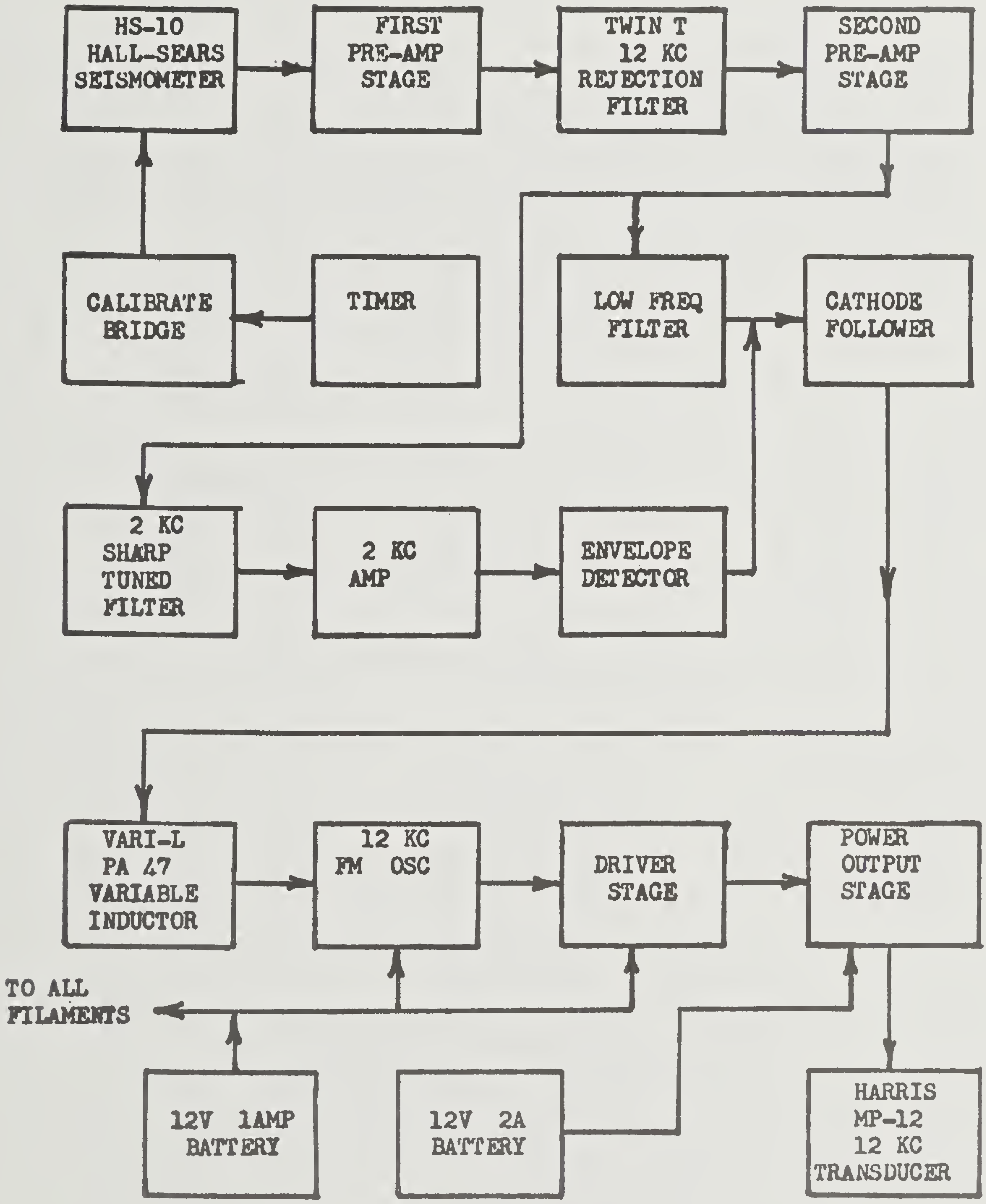


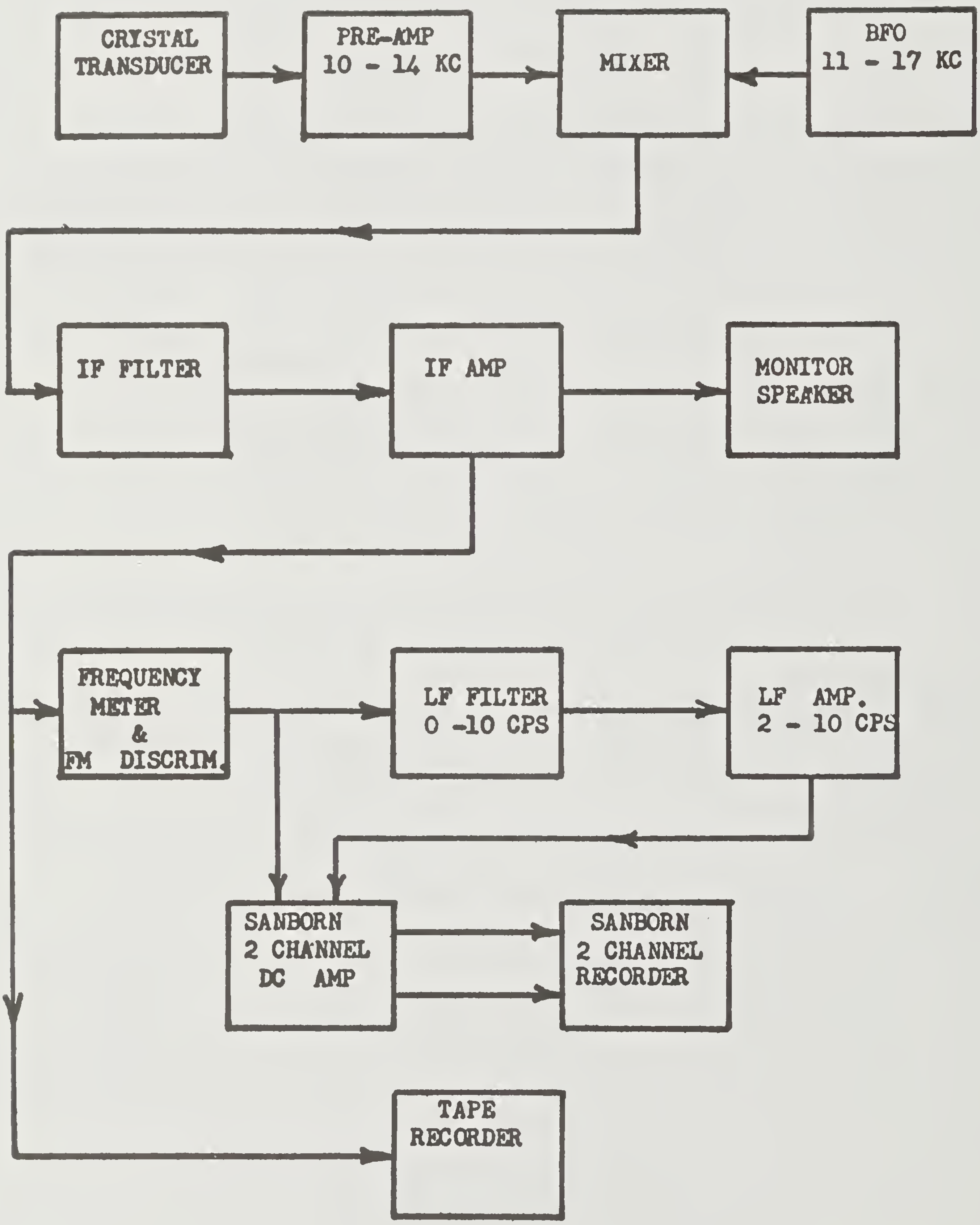
FIG. 1

TELEMETERING SYSTEM



TBS MK-3
TRANSMITTER BLOCK DIAGRAM

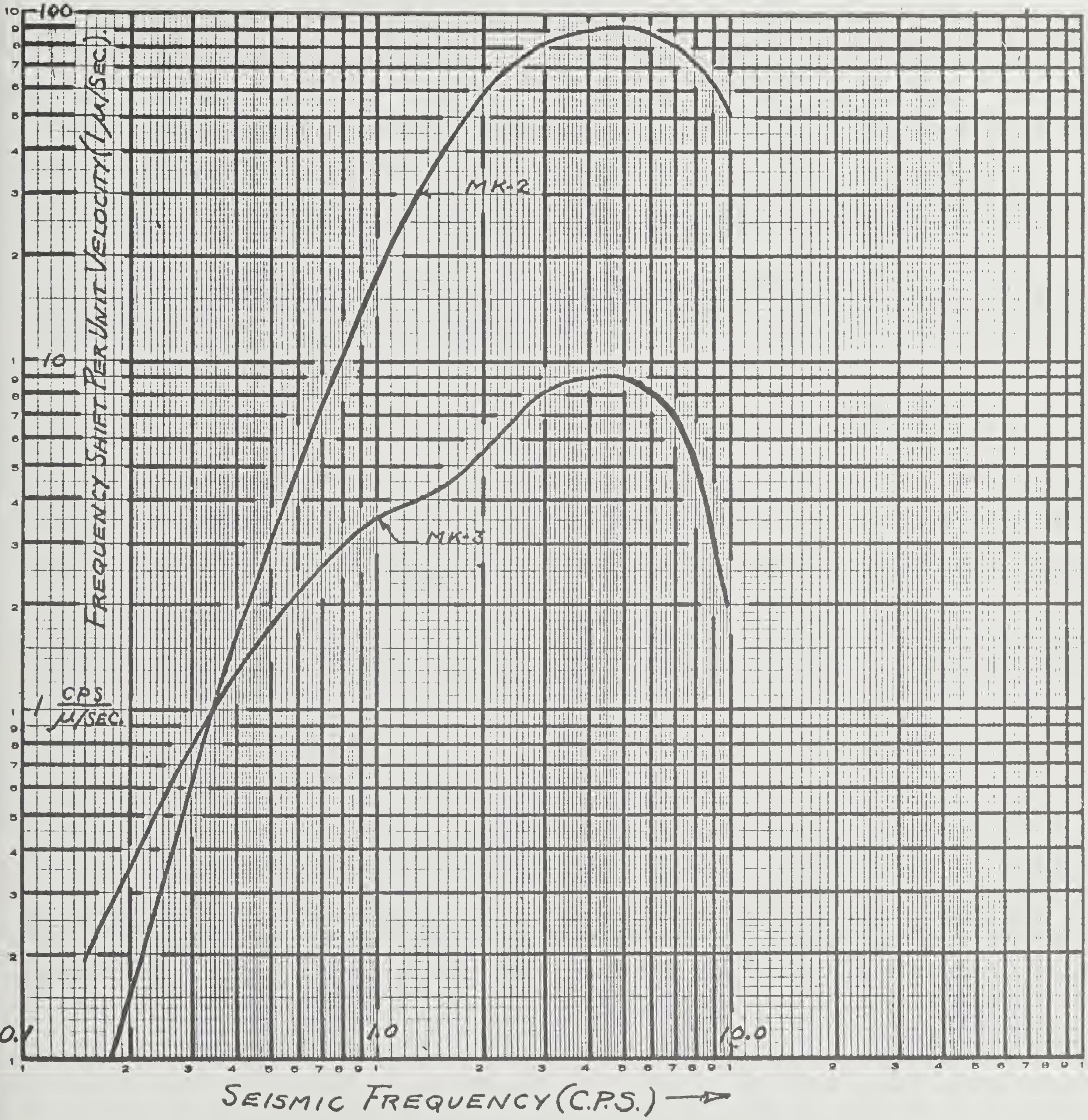
FIG. 2



TBS MK-3

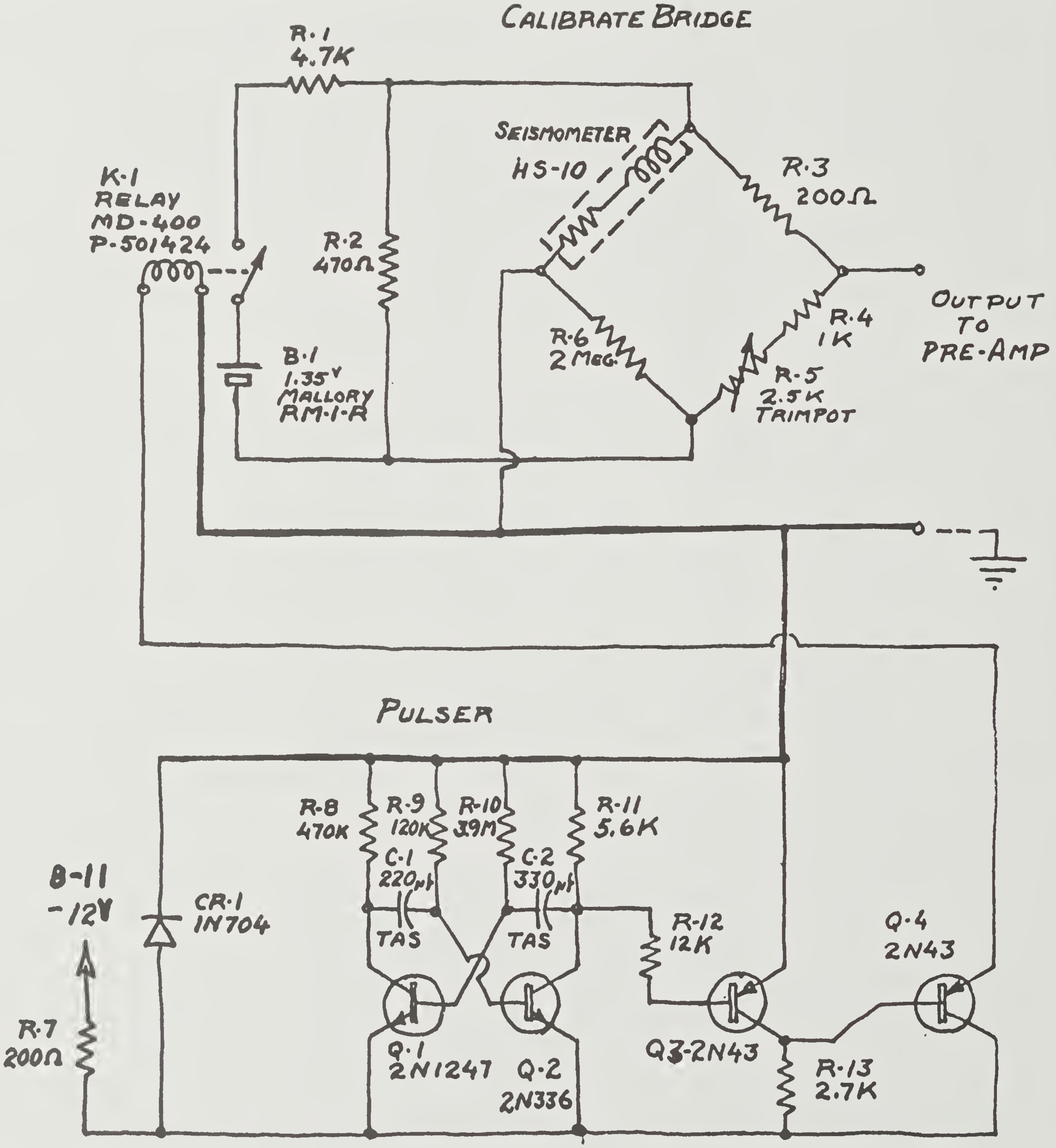
RECEIVER BLOCK DIAGRAM

FIG. 3



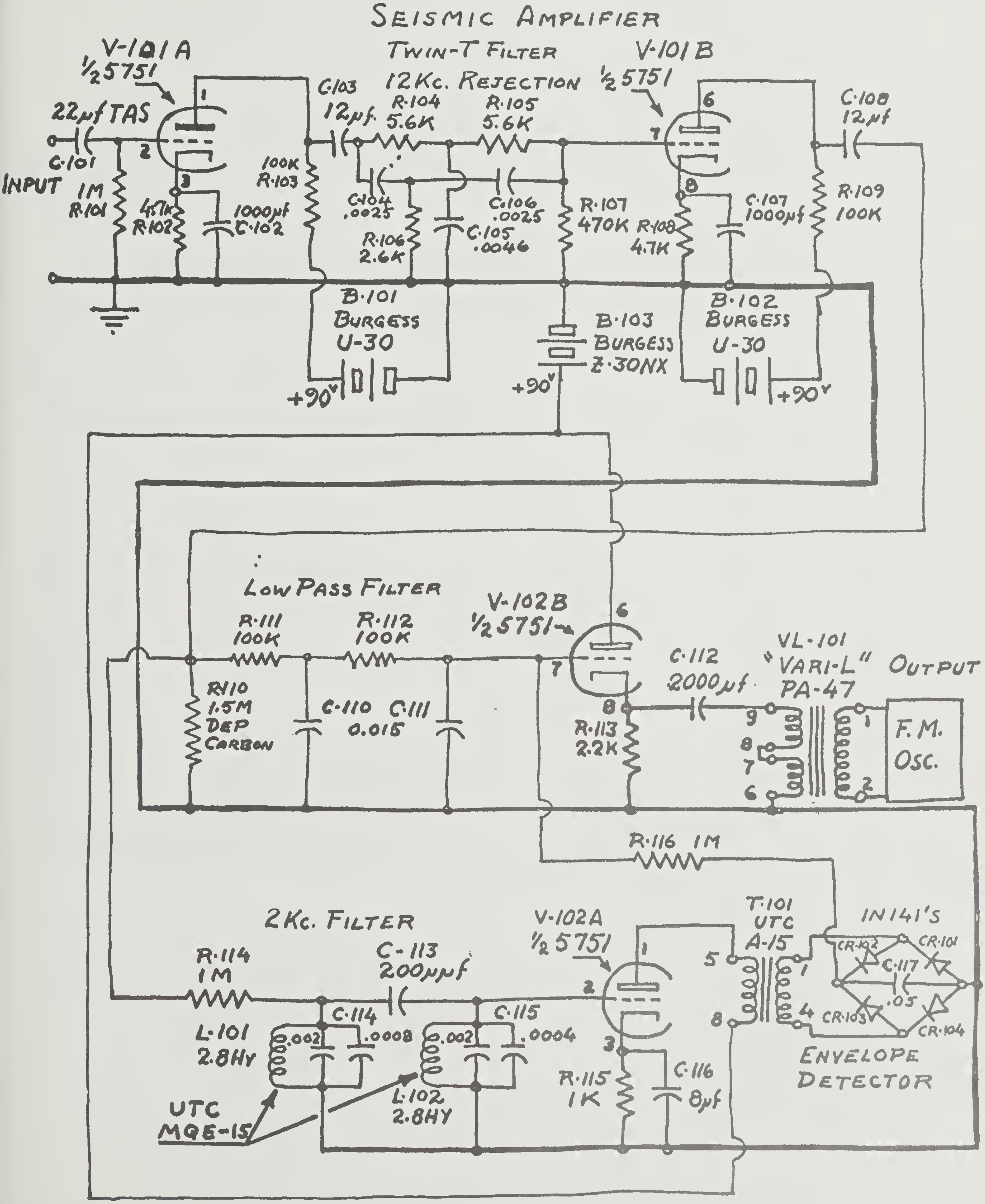
T.B.S. TRANSMITTER RESPONSE.

FIG. 4.



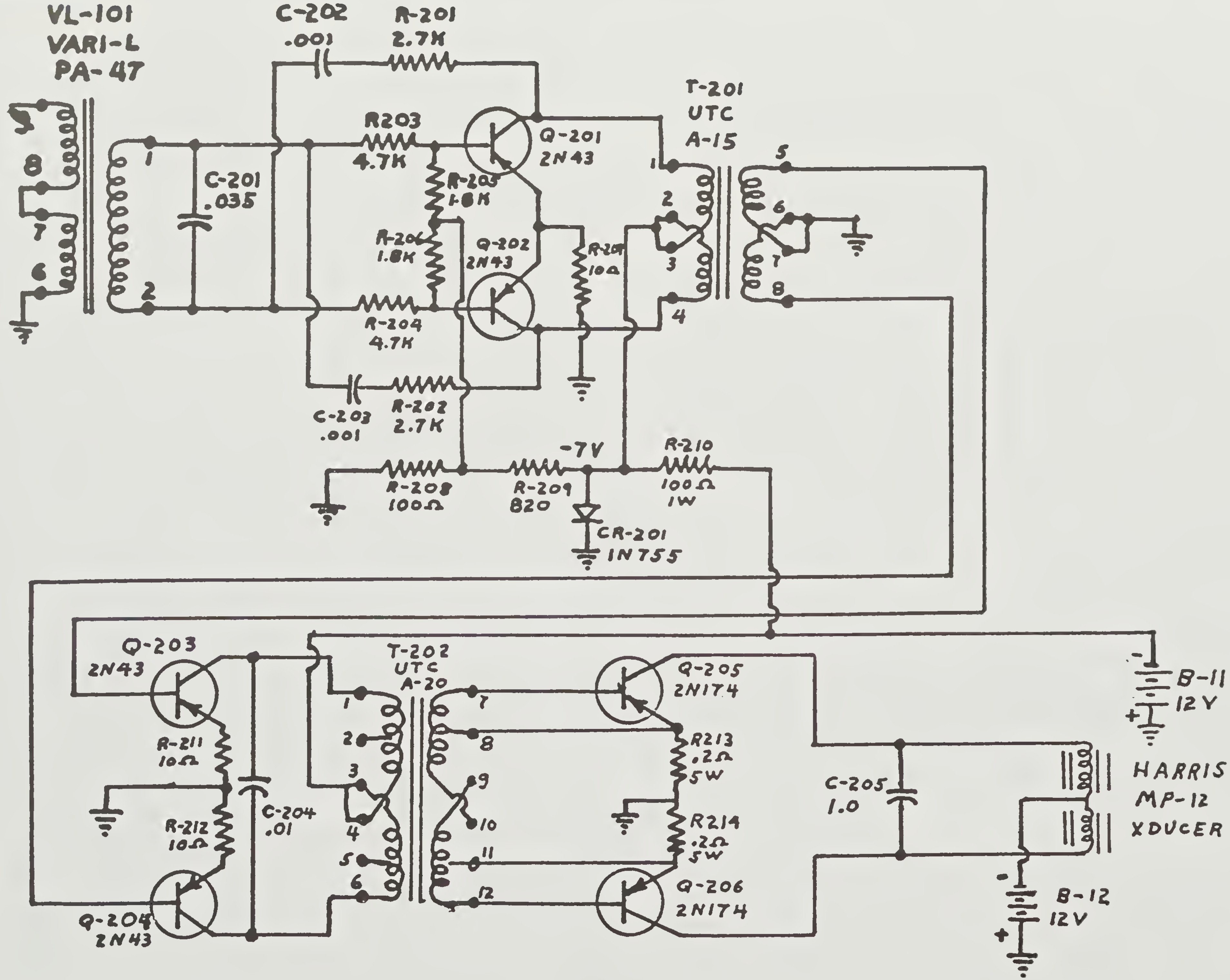
TBS MK-3 CALIBRATION CIRCUIT

FIG. 5



TBS MK-3 TRANSMITTER PRE-AMP.

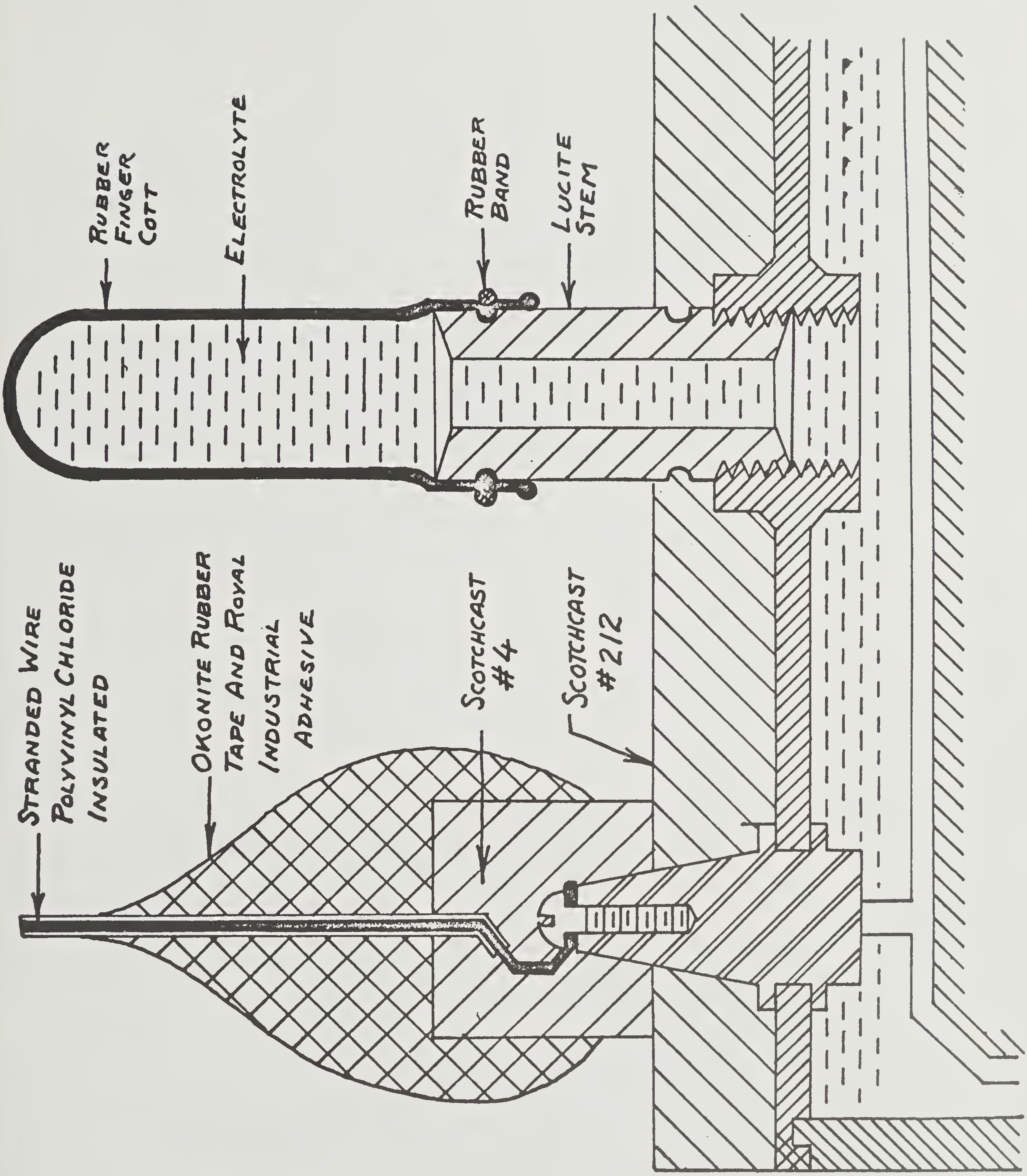
FIG. 6



TBS MK-3

FM OSCILLATOR, DRIVER, & TRANSMITTER

FIG. 7



Storage Battery Modifications For Deep Ocean Operation

FIG. 8

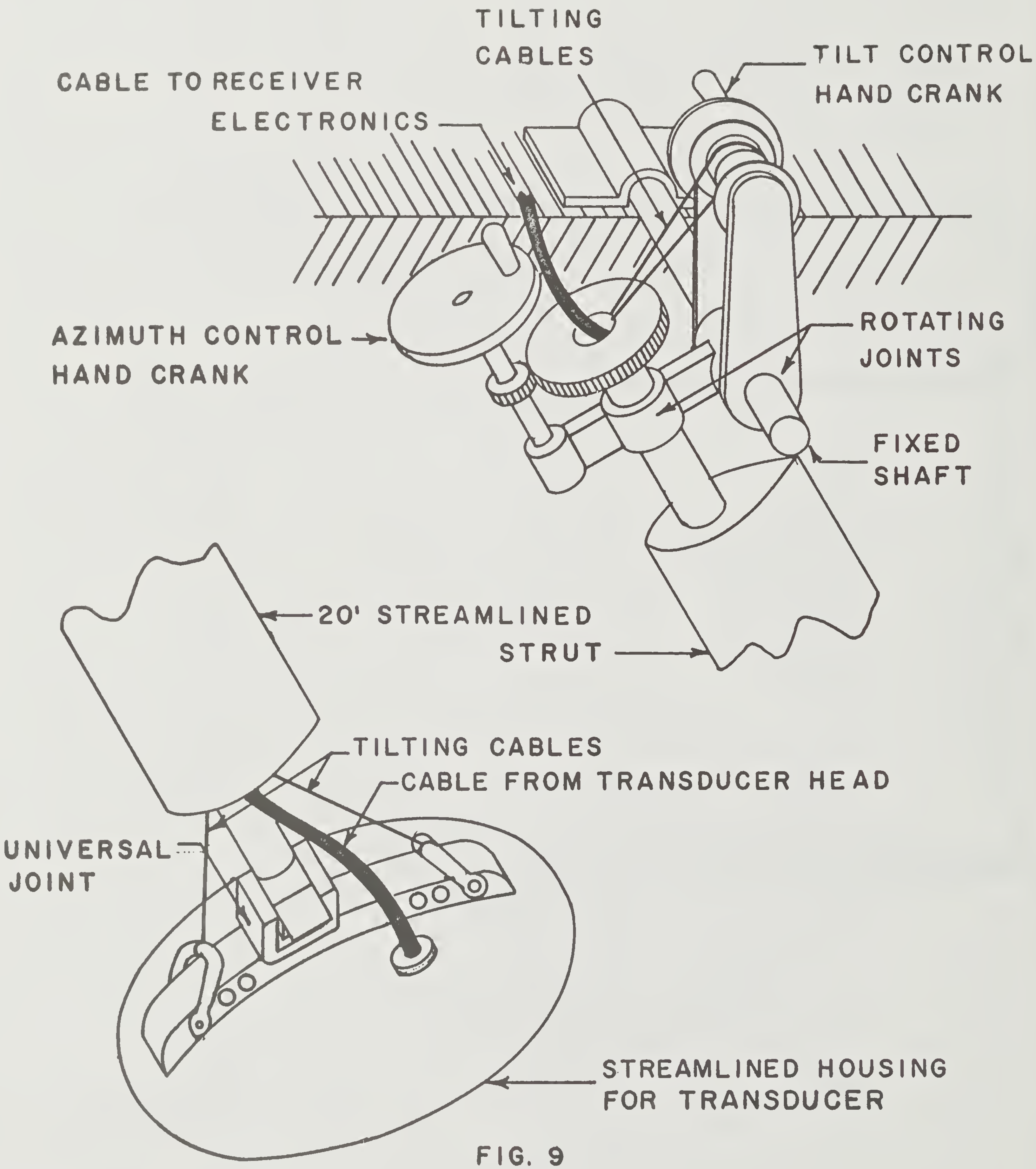
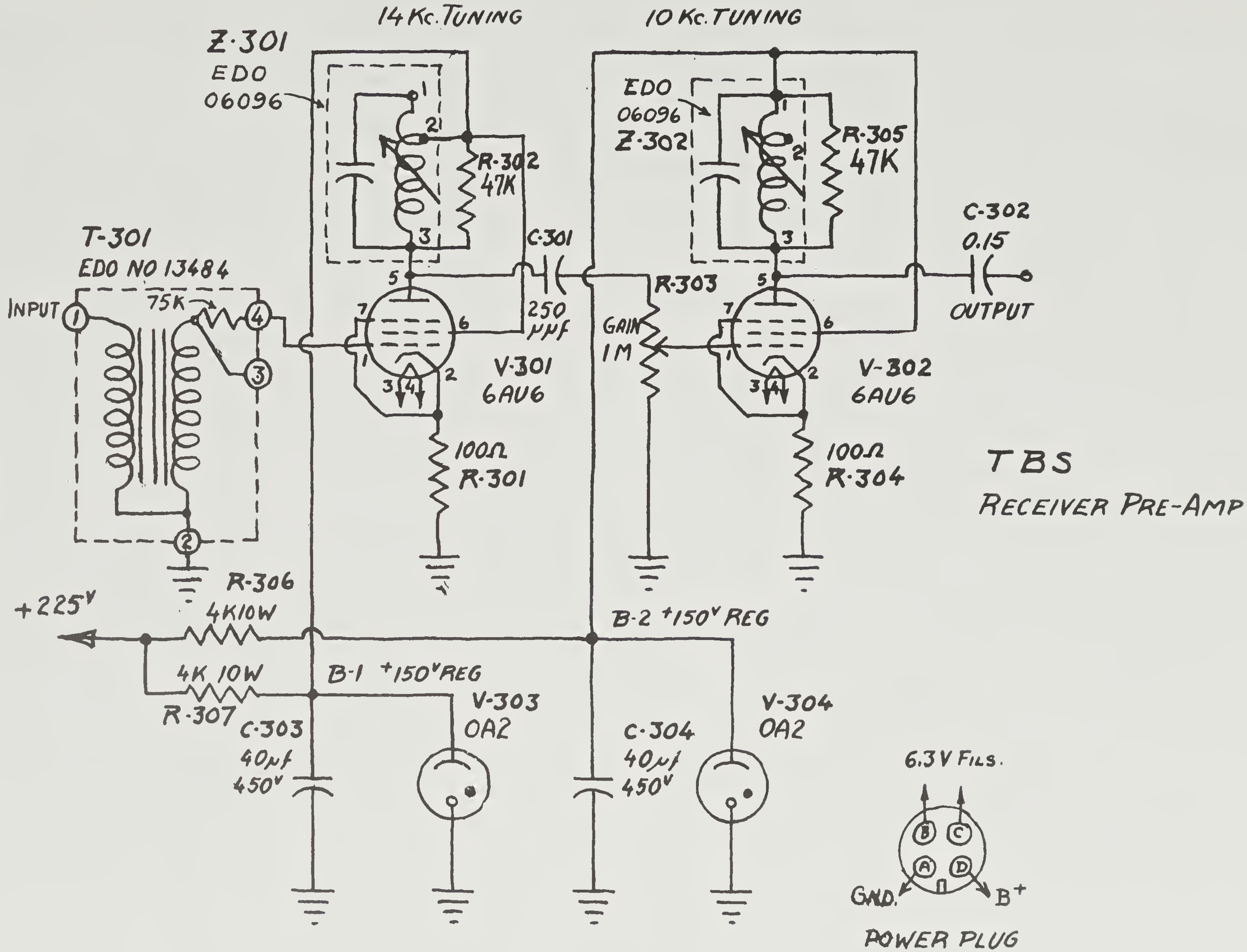


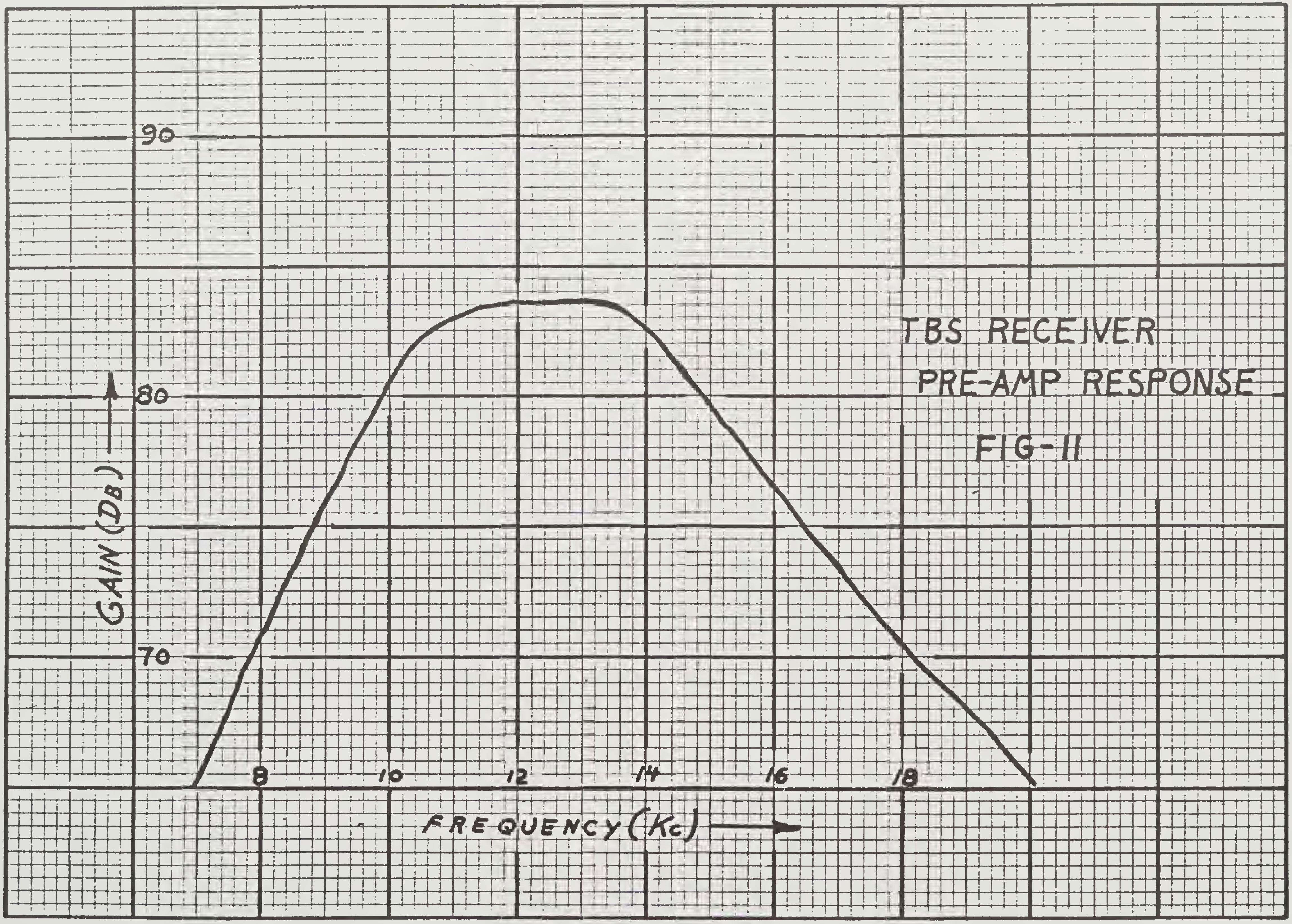
FIG. 9

TBS TRAINING UNIT FOR RECEIVING TRANSDUCER



14 Kc. TUNING
10 Kc. TUNING
Z·301
EDO
06096
EDO
06096
Z·302
R·302
47K
R·305
47K
C·302
0.15
T-301
EDO NO 13484
C·301
250 μμf
R·303
INPUT
75K
OUTPUT
GAIN
1M
V·301
6AU6
V·302
6AU6
100Ω
R·301
100Ω
R·304
TBS
RECEIVER PRE-AMP
R-306
4K10W
+225V
B-2 +150V REG
4K 10W
B-1 +150V REG
R-307
C-303
40μf
450V
V-303
OA2
C-304
40μf
450V
V-304
OA2
6.3V FILS.
GND.
B+
POWER PLUG

FIG. 10


TBS RECEIVER
PRE-AMP RESPONSE
FIG-11
GAIN (DB)
90
80
70
8
10
12
14
16
18
FREQUENCY (Kc)

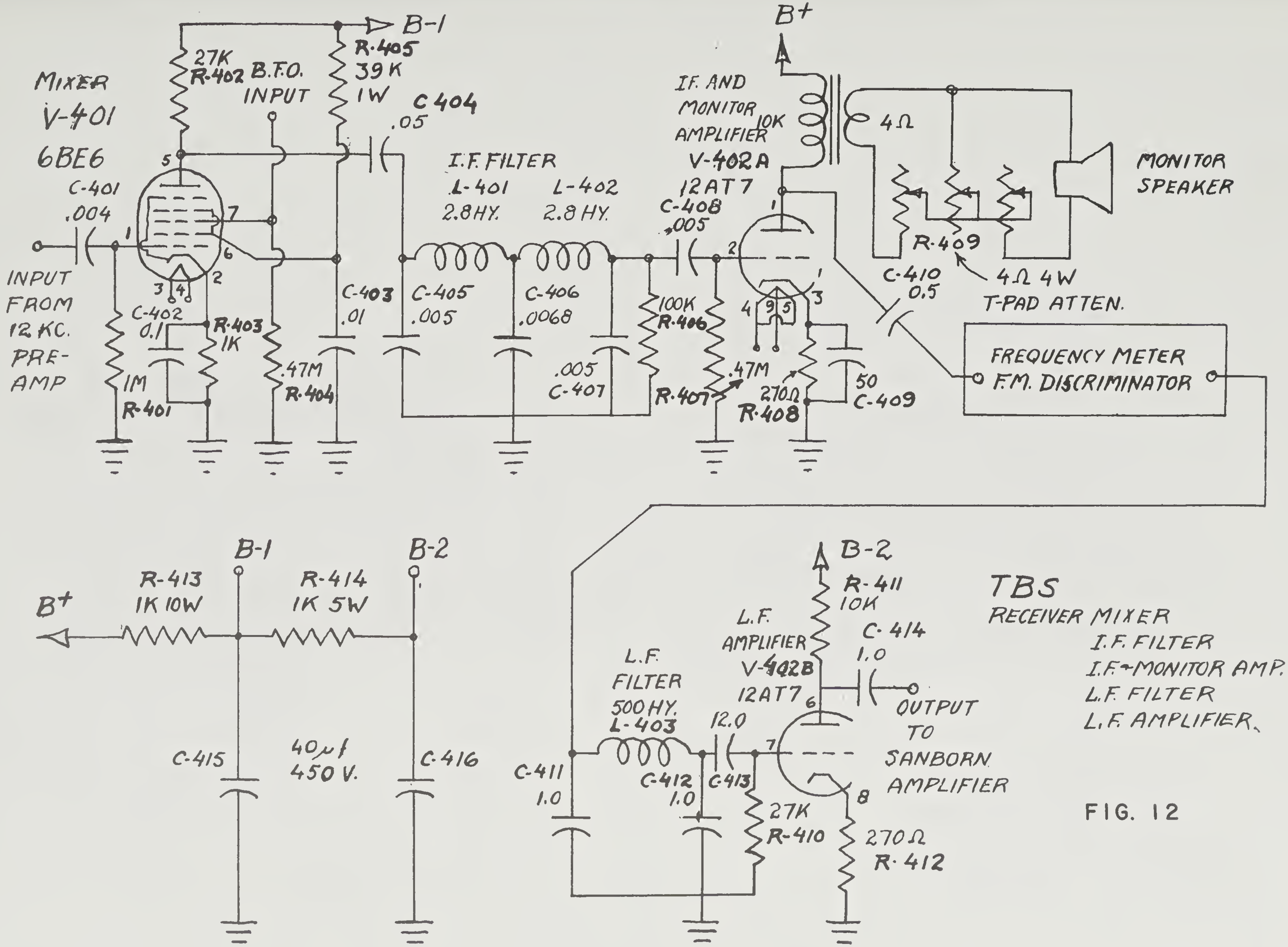
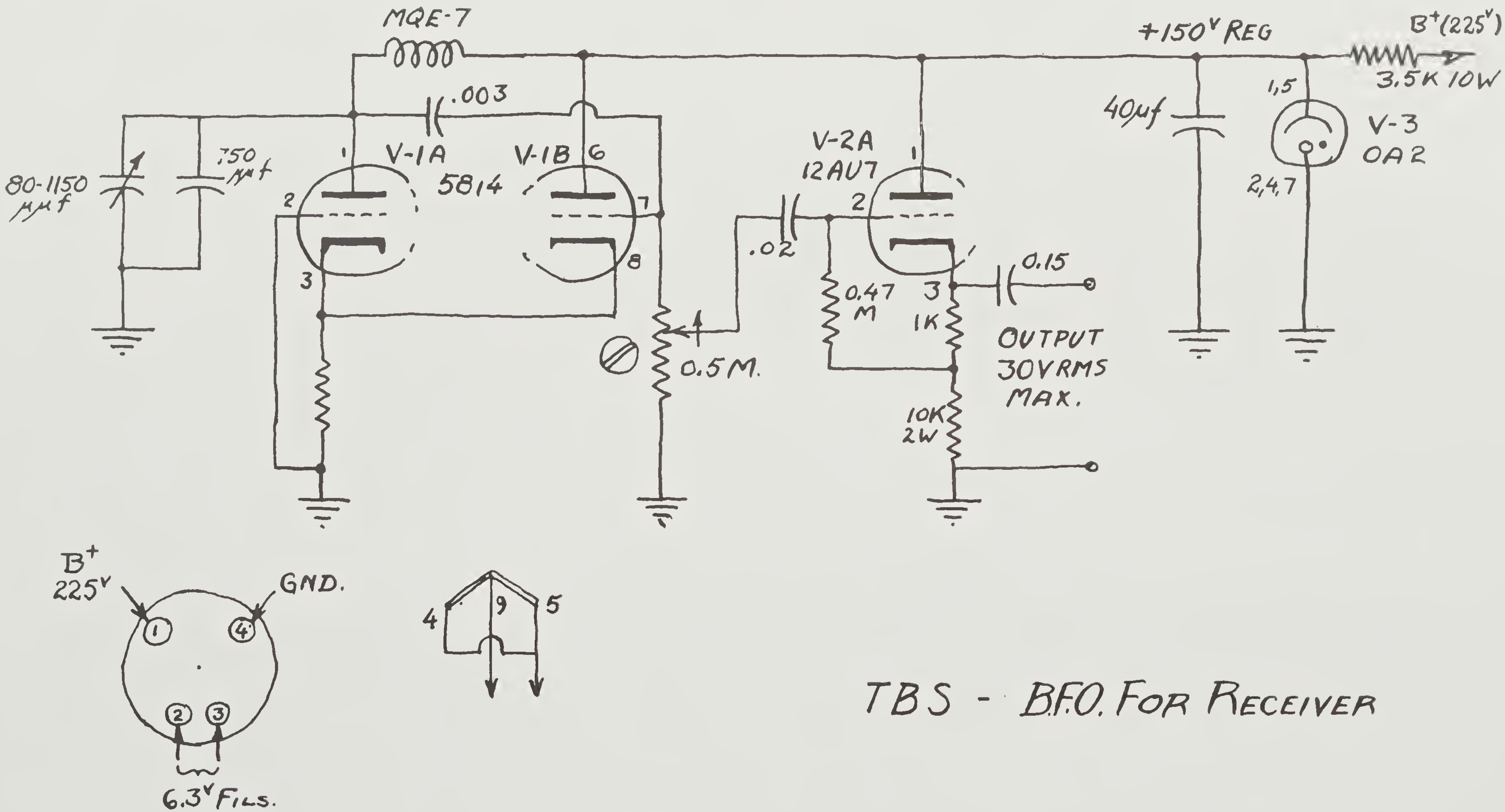
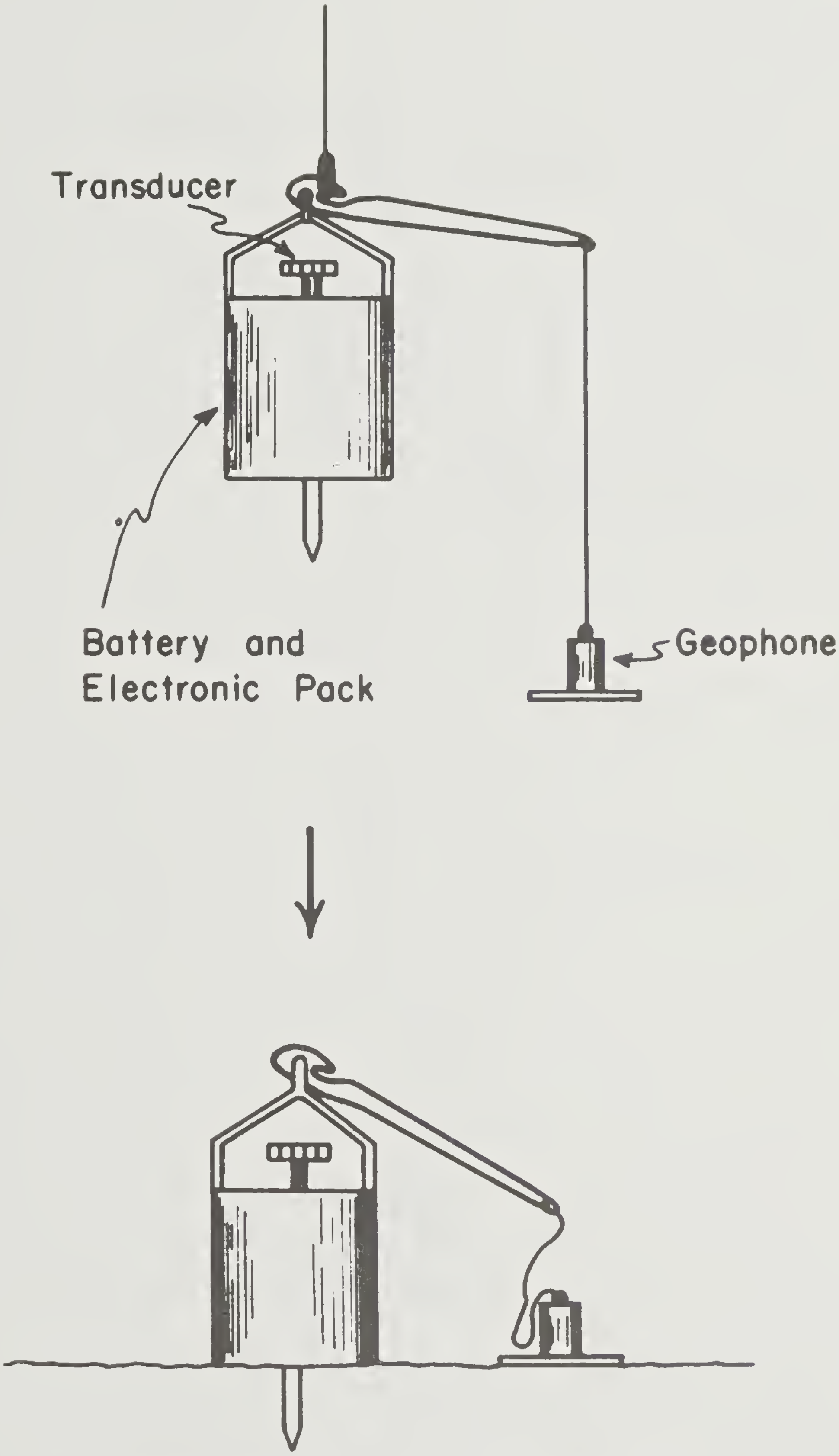

B-1
R-405
39K
1W
27K
R-402
B.F.O.
INPUT
MIXER
V-401
6BE6
C 404
.05
C-401
.004
INPUT
FROM
12 KC.
PRE-
AMP
C-402
0.1
R-403
1K
1M
R-401
.47M
R-404
C-403
.01
I.F. FILTER
L-401
2.8 HY.
L-402
2.8 HY.
C-405
.005
C-406
.0068
.005
C-407
C-408
.005
100K
R-406
.47M
R-407
270Ω
R-408
50
C-409
B+
I.F. AND
MONITOR
AMPLIFIER
10K
V-402A
12AT7
4Ω
R-409
4Ω 4W
T-PAD ATTEN.
MONITOR
SPEAKER
C-410
0.5
FREQUENCY METER
F.M. DISCRIMINATOR
B+
R-413
1K 10W
B-1
R-414
1K 5W
B-2
C-415
40μf
450 V.
C-416
B-2
R-411
10K
C-414
1.0
L.F.
AMPLIFIER
V-402B
12AT7
OUTPUT
TO
SANBORN
AMPLIFIER
L.F.
FILTER
500 HY.
L-403
12.0
C-411
1.0
C-412
1.0
C-413
27K
R-410
270Ω
R-412
TBS
RECEIVER MIXER
I.F. FILTER
I.F.-MONITOR AMP.
L.F. FILTER
L.F. AMPLIFIER.

FIG. 12



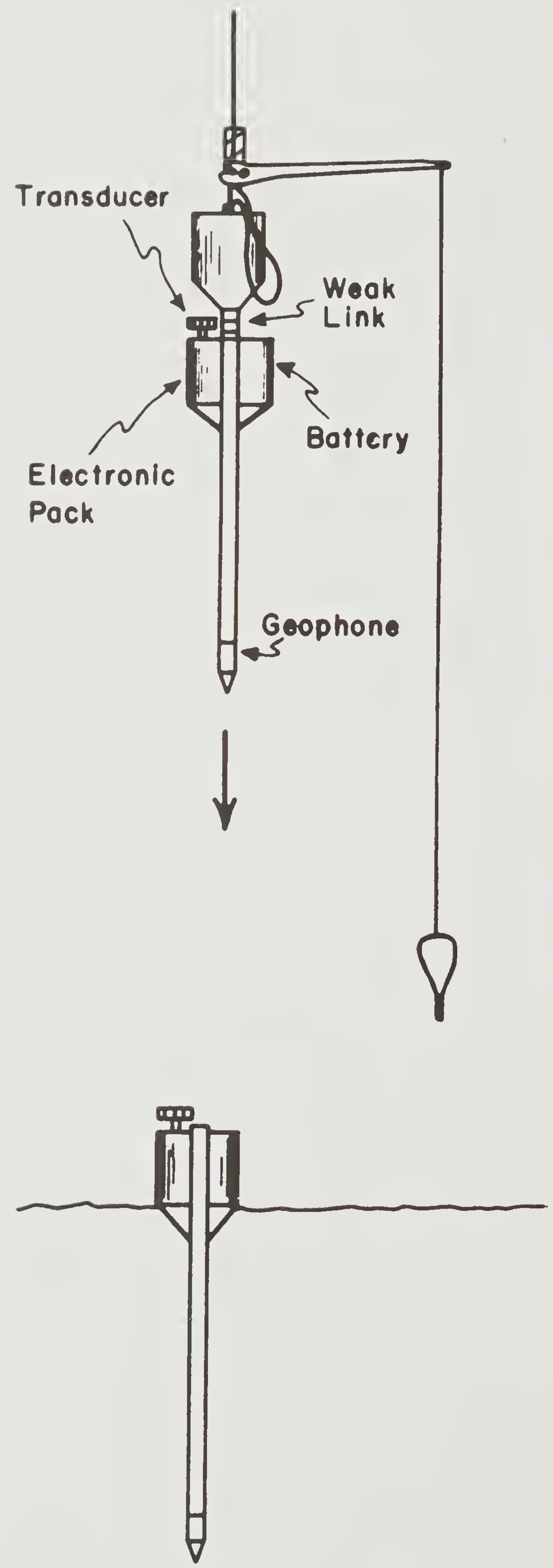
TBS - B.F.O. For Receiver

FIG. 13



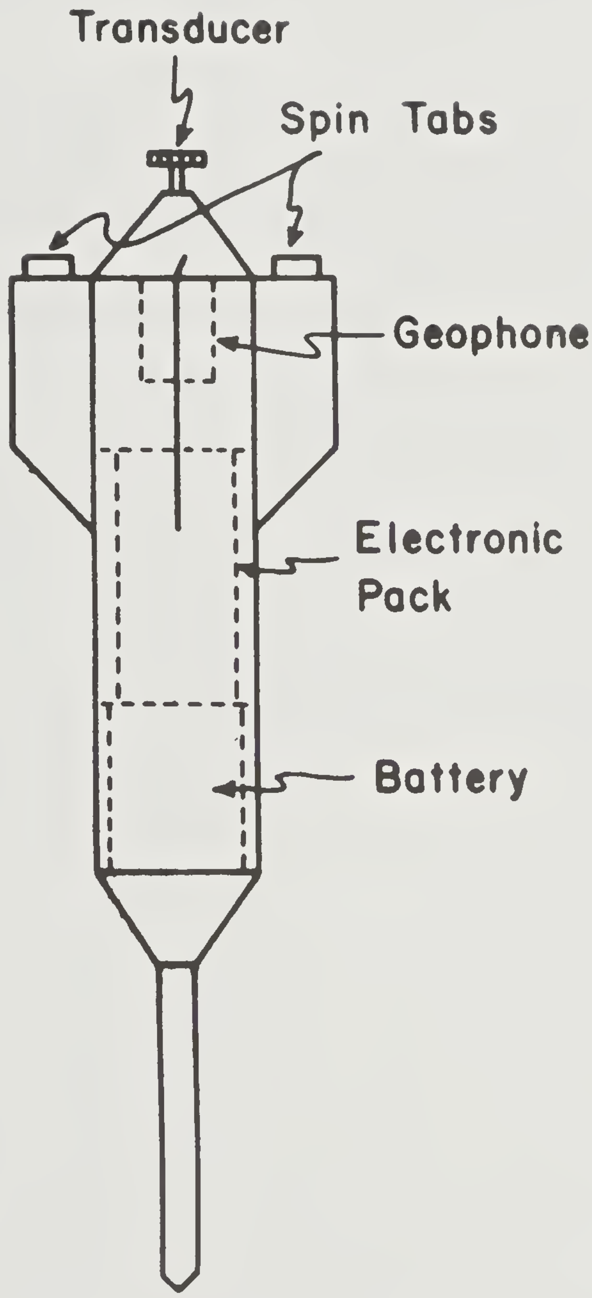
TELEMETERING BOTTOM SEISMOGRAPH
MK-1, MOD. 1

FIGURE 14



TELEMETERING BOTTOM SEISMOGRAPH
MK-1, MOD. 2

FIGURE 15



TELEMETERING BOTTOM SEISMOGRAPH
MK-2

FIGURE 16

APPENDIX II

A FILM RECORDING OCEAN BOTTOM SEISMOGRAPH

Introduction

The film recording seismograph was developed because of inherent limitations in the telemetering technique described in Appendix I. A few of these limitations follow. The length of time that data can be received from a bottom seismograph is sharply limited by the power requirements of the bottom transmitter. Contact with the unit can be lost in storms, during which the acquisition of data is most important in microseism studies. Finally, a ship must constantly remain stationed over the unit, which is an expensive operation.

The film recording seismograph has none of the above-mentioned limitations. It is contained in two pressure cases. The largest (10" inside diameter) pressure case contains a one-second Willmore vertical seismometer with attached clamping and unclamping motor, and with universal joint gravity leveling. Above the seismometer are two platforms. The first contains a solid state seismic amplifier and calibration circuit. Above this are the batteries for the clamping motors, electronics, and timing programers used in clamping and unclamping the seismometer.

The amplified seismometer signals are sent to the film recorder in a smaller (5½" diameter) pressure case via high pressure electrical feedthroughs and wire. The film recorder contains its own batteries to transport the 35mm film and to power the light source. Both pressure cases are clamped in a steel

frame which is designed so as to keep them upright when placed on bottom.

In the following pages details will be given of the transistorized seismic amplifier used that was originally designed for Lunar instrumentation but adopted for the ocean bottom work. Because of Lunar requirements, this amplifier has greater temperature tolerance than it actually needs for ocean bottom use but this can only add to its reliability. The command gain control circuits described were not used in the film recording seismograph. In addition a short description will be given of the mechanics and optics of the film recorder and of the buoying technique used to plant and to recover the instrument.

A LOW NOISE TRANSISTORIZED SEISMIC AMPLIFIER

by

Stamatios N. Thanos

The amplifier discussed here was part of the development of a four-component, soft-landing lunar seismograph designed at Lamont Observatory. This amplifier is associated with the short-period vertical seismometer. This instrument consists of a coil mounted in the flux gap of a suspended permanent magnet, which serves as the inertial mass. An auxiliary coil is wound on top of the main one, for calibration purposes. Motion of the suspended magnet relative to the stationary main coil induces a voltage proportional to the differential velocity.

A very high gain, low-noise amplifier is required to increase the minute amounts of seismometer output power up to the levels required by telemetry. In addition, the amplifier must perform satisfactorily over a specified temperature range of -20°C to +100°C, thereby necessitating the use of silicon semi-conductors throughout; it must use the minimum possible power, it should have a minimum 3-db bandwidth of 20 seconds to 10 cps output impedance of less than 500 ohms and an output swing capability of 0-5 volts, consistent with telemetry requirements. Since the dynamic range of the telemetry is specified as 46 db, the minimum detectable output is 25 mv. The transducer output across its damping resistance is on the order of 0.6 uv p-p per mu p-p ground displacement at 1 cps.

In view of the extremely low frequencies involved, the chopper-amplifier is probably the best choise in seismic work.

Very low noise levels may be achieved with good mechanical or photoelectric choppers. These, however, had to be ruled out in this case because of power, environmental and reliability requirements. Solid-state choppers, on the other hand, do not offer much promise in achieving the desired noise levels.

Figure 1 shows a functional block diagram of the amplifier. A compromise was reached in a design that employs a solid-state chopper-amplifier preceded by a direct coupled, low-noise preamplifier with a single, low-frequency coupling between the two. Thus D-C drift from the preamplifier is not amplified further by the carrier amplifier. In order to utilize the advantages of a balanced arrangement in the preamplifier, the seismometer main coil was center-tapped, thus providing a push-pull output. The output of the preamplifier is filtered and applied to the modulator followed by another stage of push-pull amplification. The modulated signal is then applied, through the attenuator to the carrier (A-C) amplifier. It is then demodulated and filtered. The calibrator provides a voltage step on command which is applied through another attenuator to the auxiliary coil. The step is subsequently turned off by another command.

Figure 2 shows the equivalent circuit of the preamplifier used in deriving feedback relations. The preamplifier consists of two direct-coupled differential stages with overall direct feedback. The feedback stabilizes the operating point, the current gain and the input impedance presented to each half of the center-tapped transducer coil. In the left corner of the

figure is the relation between R_i (input resistance), A_v (voltage gain) and R_{fb} (feedback resistance). The amount of feedback is choeen to adjust the amplifier input impedance to that required for damping the seismometer without the use of an external damping resistor. Thus, the maximum amount of power is transferred to the input of the amplifier. The voltage gain is stabilized through local degeneration in both stages.

A complete analysis of the voltage gain of the circuit shows that, for the worst combination of transistor parameters, the gain may vary by approximately 2:1, resulting in an input impedance variation of ± 40% over the specified temperature range. The corresponding spread in damping factor ranges from + 21% to -16% about the design center. This spread may be reduced to ± 10% if the feedback resistors are selected for a particular amplifier to provide the correct damping at room temperature.

Figures 3 through 5 show the complete circuit diagrams as modified for use with the film recorder. Figure 6 shows the frequency response curve with -3 db points at .035 and 22 cps.

Figure 7 shows the output noise with an overall gain of 1/2 million recorder sensitivity 200 mv/cm; recorder speeds of: A. 0.5 mm/sec; B. 1 mm/sec; C 10 mm/sec; D. 100 mm/sec. For 90% of the time noise does not exceed 100 mv, corresponding to an equivalent input of 0.2 uv p-p.

Figure 8 shows the output with a 1 uv p-p input of periods. A. 20 seconds; B. 10 seconds; C. 1 second; D. 0.1 second sensitivity 200 mv/cm and gain of 1/2 million.

Figure 9 shows the output with a 1/4 uv input of the same periods as in Figure 8. In particular, the 1 second input is detected with a S/N ratio of about 4:1. Thus, for the given transducer sensitivity of 0.6 uv/mu p-p at 1 second, it appears possible to detect 1 Anstrom p-p ground motion at 1 second with unity S/N ratio.

It should be emphasized at this point that, except for matching, no other selection of input transistors was made. A number of units have been subsequently built and used in the field. Noise measurements on these gave results substantially identical to the above.

The power consumption of the amplifier, exclusive of the carrier oscillator and the attenuator, is 75 mw. The attenuator requires 40 mw. The oscillator, which is shared by all four components, draws 230 mw. Of this amount, not more than 50 mw may be charged to the short-period amplifier.

In conclusion, the development of this amplifier has demonstrated the feasibility of designing solid-state amplifiers for detection of fractional microvolt signals at extremely low frequencies, where 1/f noise is the predominant factor. Furthermore, stringent environmental requirements may be satisfied without sacrifice of performance.

The amplifier can be used in many applications where size, weight, power drain and reliability in adverse environments are important. Remote calibration and gain change are possible. At Lamont it is being used in conjunction with ocean bottom and deep well seismographs.

The bandwidth can easily be changed to suit particular requirements and different impedance coils can readily be accommodated. For single-ended coil operation, one of the inputs may be grounded.

THE MECHANICS AND OPTICS OF A 35mm FILM RECORDER

Figure 10 shows a schematic scale drawing of the first film recorder developed for ocean bottom use at Lamont. One hundred feet of film is transported from the supply reel to the take-up reel by a 12-volt battery powered motor. Gearing was selected to give a film transport speed of approximately 2 feet per hour. Fifty hours of recording are possible by making a single trace on 100 feet of film.

The optics shown in Figure 10 produced a mean spot diameter of 10 microns which, combined with the film speed, results in a maximum frequency resolution of 4 cycles per second. This small spot size was due to the relatively short optical arm. The galvanometer used was a Geotech model 4100 with a free period of 1/5 of a second and a sensitivity of 1.34 microamps per mm with a mirror to film distance of 2.23 cm. The light source was an L-12-12 pinlight drawing 12 milliamps at 1.2 volts.

Figure 11 shows a photograph of a new indexing film recorder. The film transport speed is 5 feet per hour, resulting in a maximum frequency resolution of up to 10 cycles per second. An indexing motor and screw moves the film carriage about a pivot relative to the galvanometer mirror after the film has been transported to the take-up reel. The drive motors reverse and the film re-winds recording data in the opposite direction. This sequencing continues until 40 traces have been recorded across the film. The total record length is 33.3 days with a

maximum trace amplitude of 4.75 mm. This recorder fits into the same 5½-inch inside diameter pressure case used by the non-indexing film recorder.

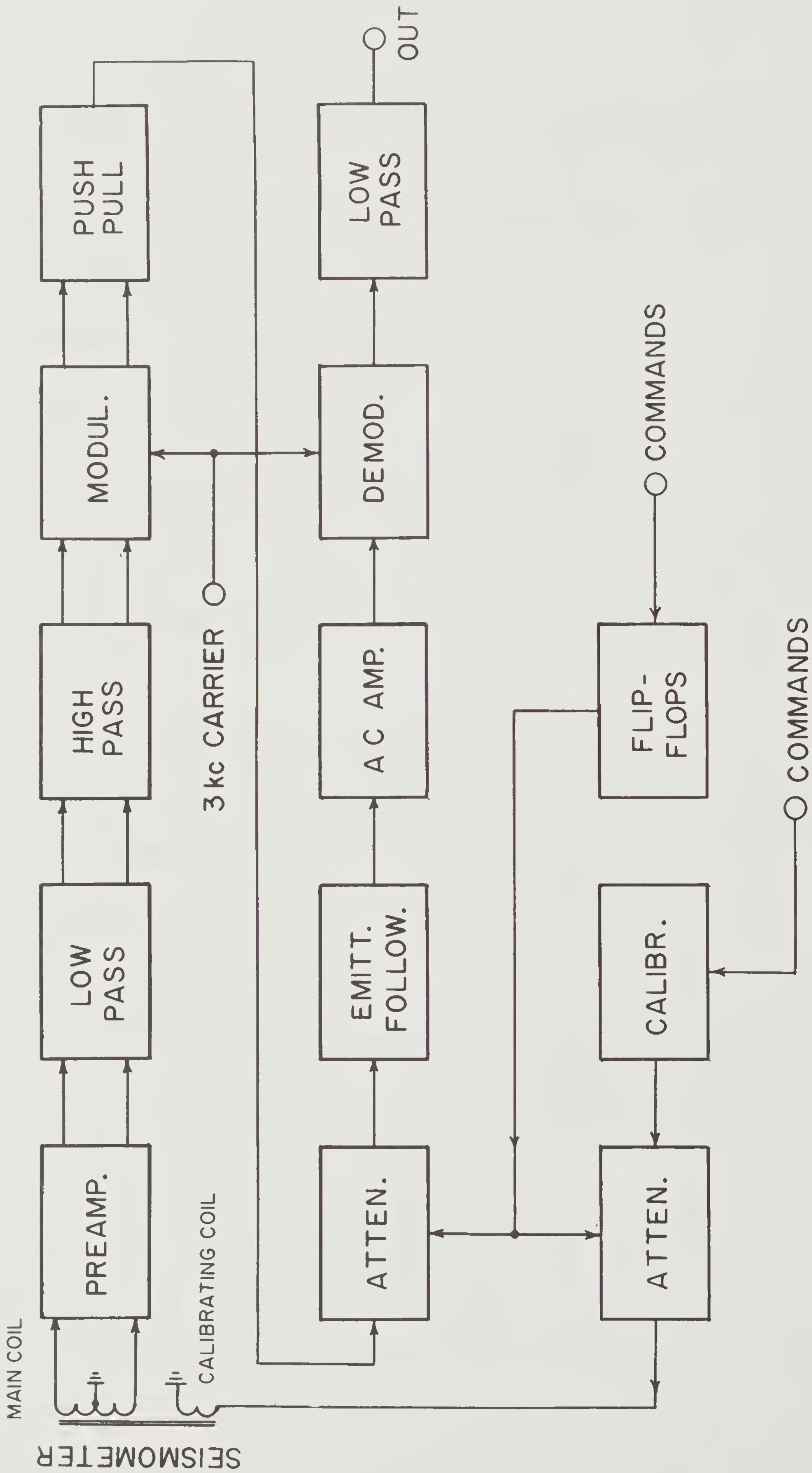
BUOYING TECHNIQUE

Figure 12 is a sketch of the procedure used to lower the film recording seismograph to the ocean floor. The left portion of the figure shows the 500-pound decoupling weight with an attached acoustic pinger. The pinger assists in setting down the decoupling weight as far as possible from the seismograph but with slack in the manila line between the two.

The pinger operates once each second as long as the seismograph keeps tension on the manila line. These pings are picked up on standard echo sounding equipment and displayed on the ship's precision depth recorder. The position of the reflected and direct waves are used to gauge the distance from the bottom. The appearance of the echo from bottom close to the direct pinger wave indicates that touchdown is near. Seismograph touchdown is signaled by the cutoff of the pinger signal. The weight is then lowered 100 feet farther and stopped until the horizontal motion of the weight produced by the ship's drift takes up the slack in the manila line and turns on the pinger. This procedure is repeated until the weight has been lowered almost to bottom and displaced almost 600 feet horizontally from the seismograph. The weight is then rapidly lowered to bottom leaving slack line between it and the seismograph.

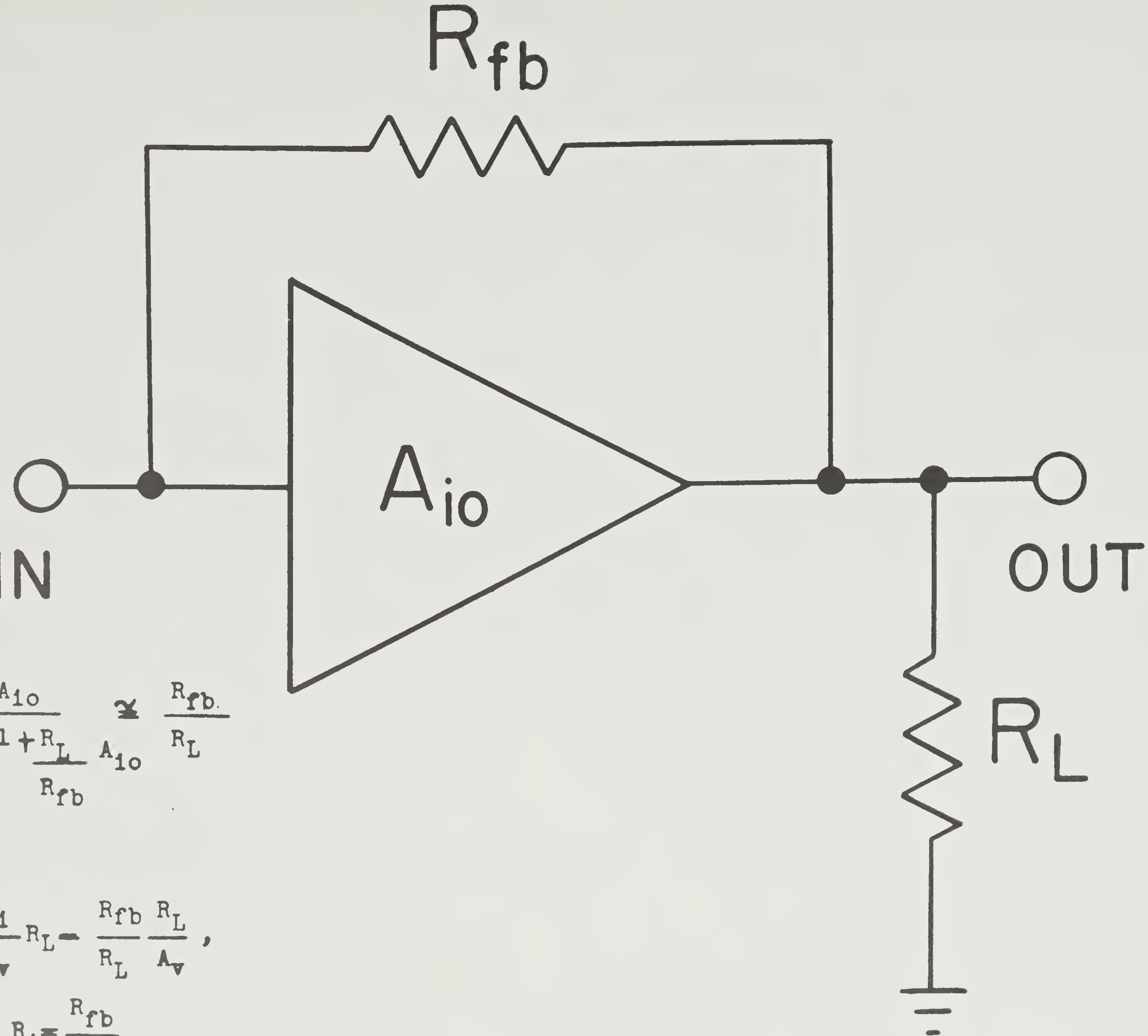
During the lowering of the seismograph, the seismometer has been clamped. Six hours after the pressure case has been sealed on deck, the programming timer starts the unclamping motor and frees the seismograph mass. Lowering takes from 2 to 3 hours in 2000 to 3000 fathoms of water so that adequate time is available to complete the maneuver and attach the buoy before the instrument begins to record. The right portion of the figure shows the seismograph and weight on bottom with the polypropelene line leading to the buoy at the surface. A relatively small buoy can be used because of the slight positive buoyancy of the polypropelene.

This technique is still in the development stage and requires a high level of judgment and seamanship on the part of the captain and of the crew. The R.V. SIR HORACE LAMB of Columbia University's Geophysical Field Station in Bermuda has performed this maneuver four times without mishap. This demonstrates not only the feasibility of the technique but also the professional performance of Captain McCann and his crew.



MAIN COIL
CALIBRATING COIL
SEISMOMETER
PREAMP.
LOW PASS
HIGH PASS
MODUL.
PUSH PULL
3 kc CARRIER
ATTEN.
EMITT. FOLLOW.
A C AMP.
DEMOD.
LOW PASS
OUT
COMMANDS
FLIP-FLOPS
COMMANDS
CALIBR.
ATTEN.

Figure 1.



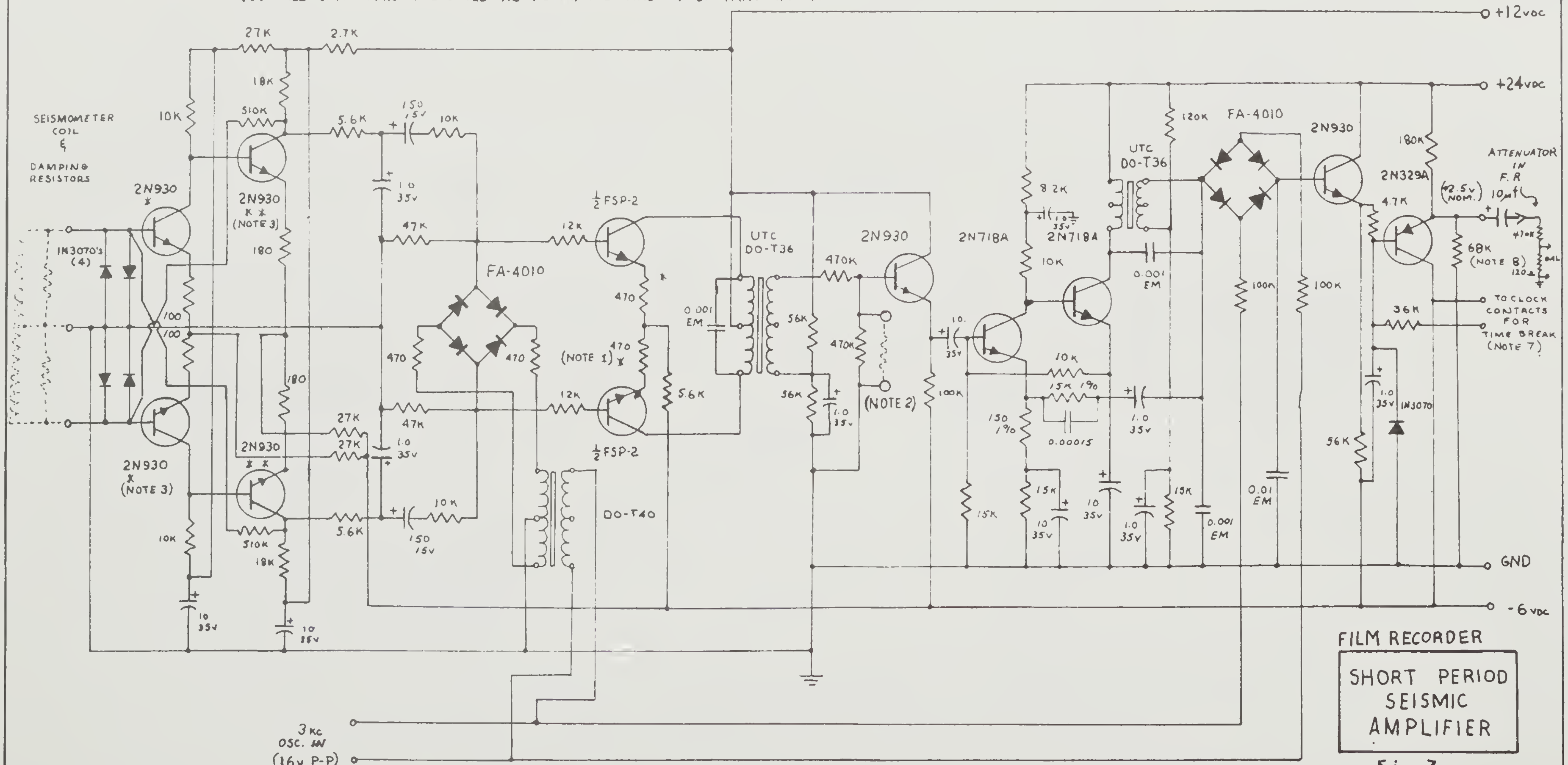
$$|A_i| = \frac{A_{io}}{1 + \frac{R_L}{R_{fb}} A_{io}} \cong \frac{R_{fb}}{R_L}$$

$$R_i = \frac{A_i}{A_v} R_L = \frac{R_{fb}}{R_L} \frac{R_L}{A_v},$$

$$\text{or} \quad R_i = \frac{R_{fb}}{A_v}$$

Figure 2.

NOTES: (1) MUST BE MATCHED IN LAB FOR CARRIER NULL AT ATTENUATOR TERMINALS.
(2) ATTENUATOR RESISTOR FOR SETTING AMPLIFIER GAIN.
(3) MATCHED PAIRS
(4) ALL RESISTORS $\frac{1}{4}$ WATT, 5%
(5) ALL CAPACITORS MARKED EM ARE DIPPED MYLAR CAPACITORS.
(6) ALL CAPACITORS INDICATED AS POLARIZED ARE TAS. TANTALYTICS.
(7) FOR FRBS APPLICATION A 1 VOLT (20%) STEP MAY BE PRODUCED BY CONNECTING THESE TERMINALS TO SPST NORM OPEN CLOCK CONTACTS.
(8) 68K RESISTOR FOR SYMMETRICAL CLIPPING OF OUTPUT AT 0 & +5V LEVELS.

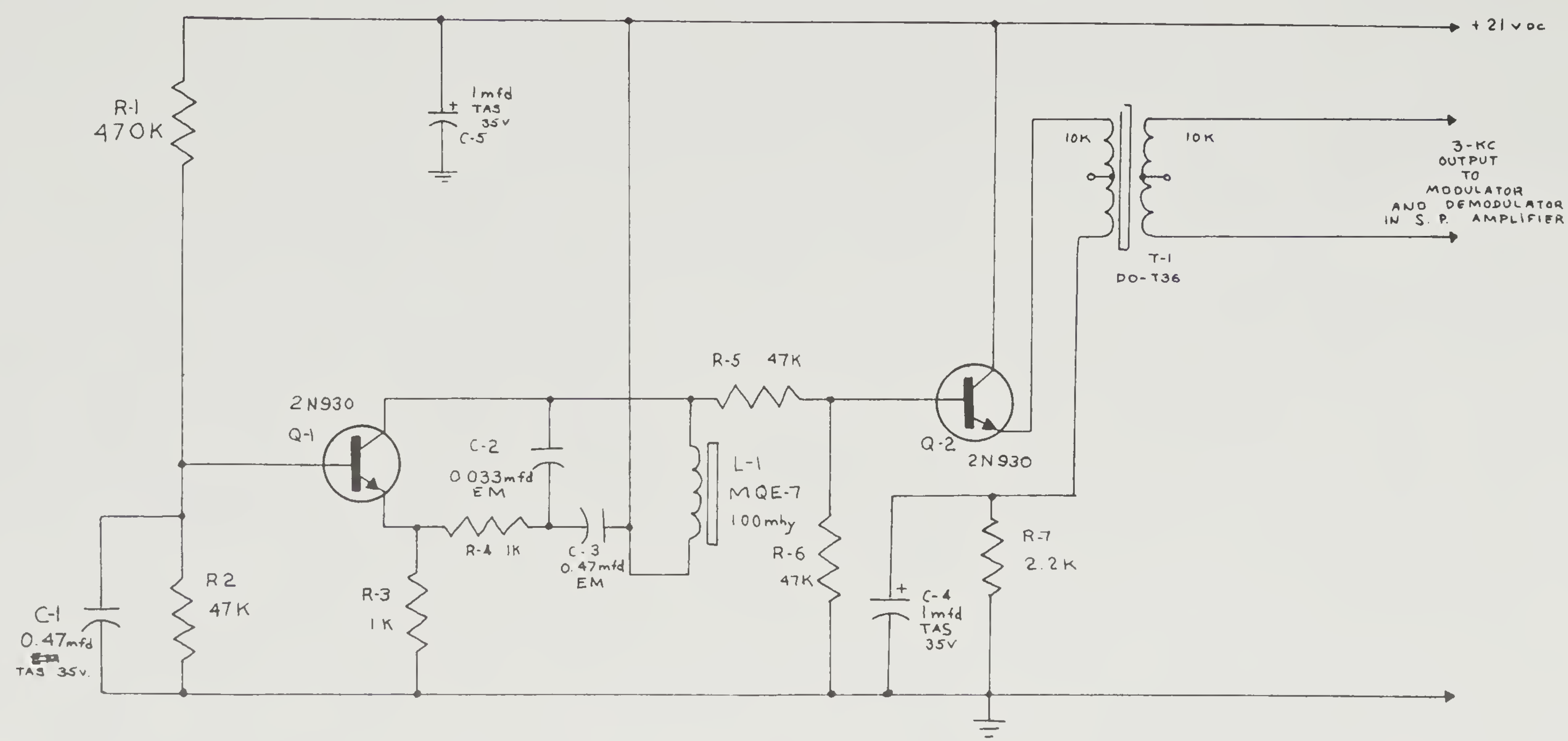


FILM RECORDER

SHORT PERIOD SEISMIC AMPLIFIER

Fig. 3

DESIGN BY S. N. THANOS   DRAWN BY J. TREVOR   7-25-62

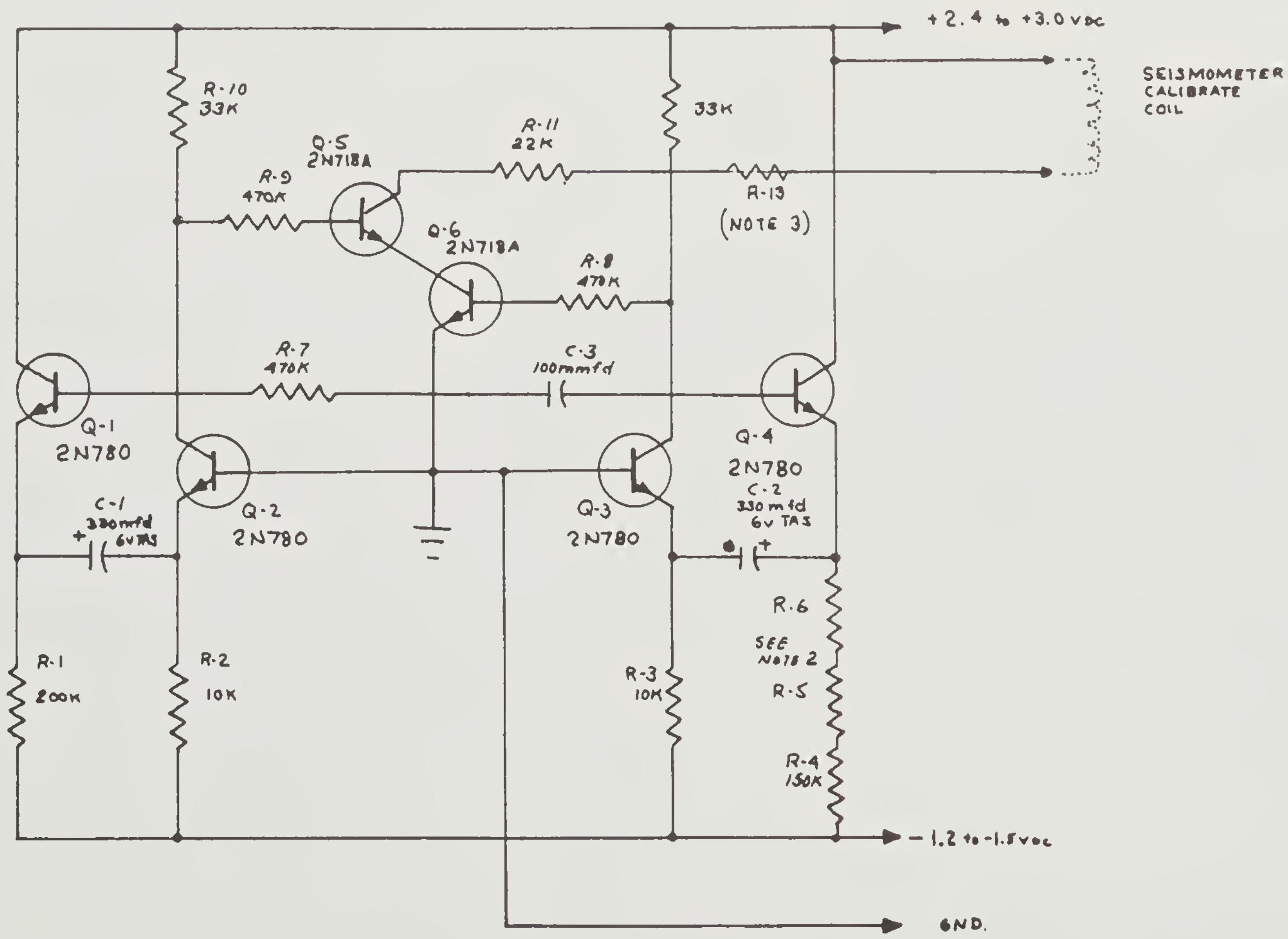


NOTES:

1) CAPACITORS DESIGNATED AS EM ARE DIPPED MYLAR 600VOLT WITH ±10% TOLERANCE
2) ALL RESISTORS ±5%

Fig. 4.

3KC OSCILLATOR FOR S.P. AMP. USED IN FRBS SYSTEM MK II					
Lamont Geological Observatory of Columbia University Palisades New York					
Dwg No:			Mod: 2		
Drawn by: J. TREVOR			Checked by		
Date 9-17-62			Scale		
Revisions					
No.	Date	By	No	Date	By



N<u>OTES</u>:

1) All resistors are ¼ WATT; ±5% tolerence
2) These resistors are chosen so that period of the second multivibrator is close to that of the first. Approx. Value 27K.
3) Value depends on amplifier gain setting.

SEISMOMETER CALIBRATOR used in FRBS SYSTEM MK II	
Lamont Geological Observatory of Columbia University, Palisades New York	
Dwg. No:	Mod:
Drawn by: J. TREVOR	Checked by:
Date: 9-17-62	Scale: ————

Revisions

No.	Date	By	No.	Date	By

fig. 5

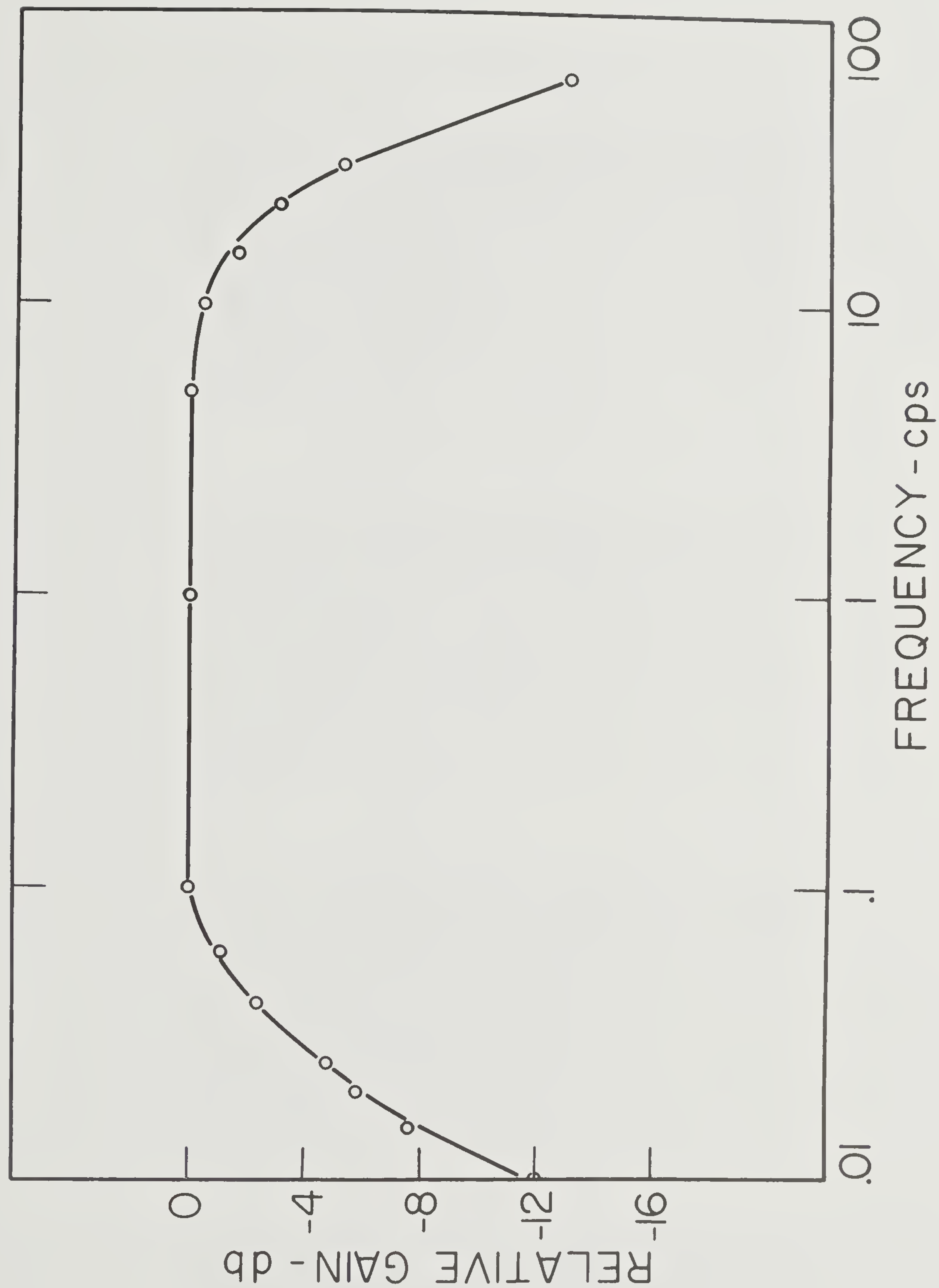


Figure 6.

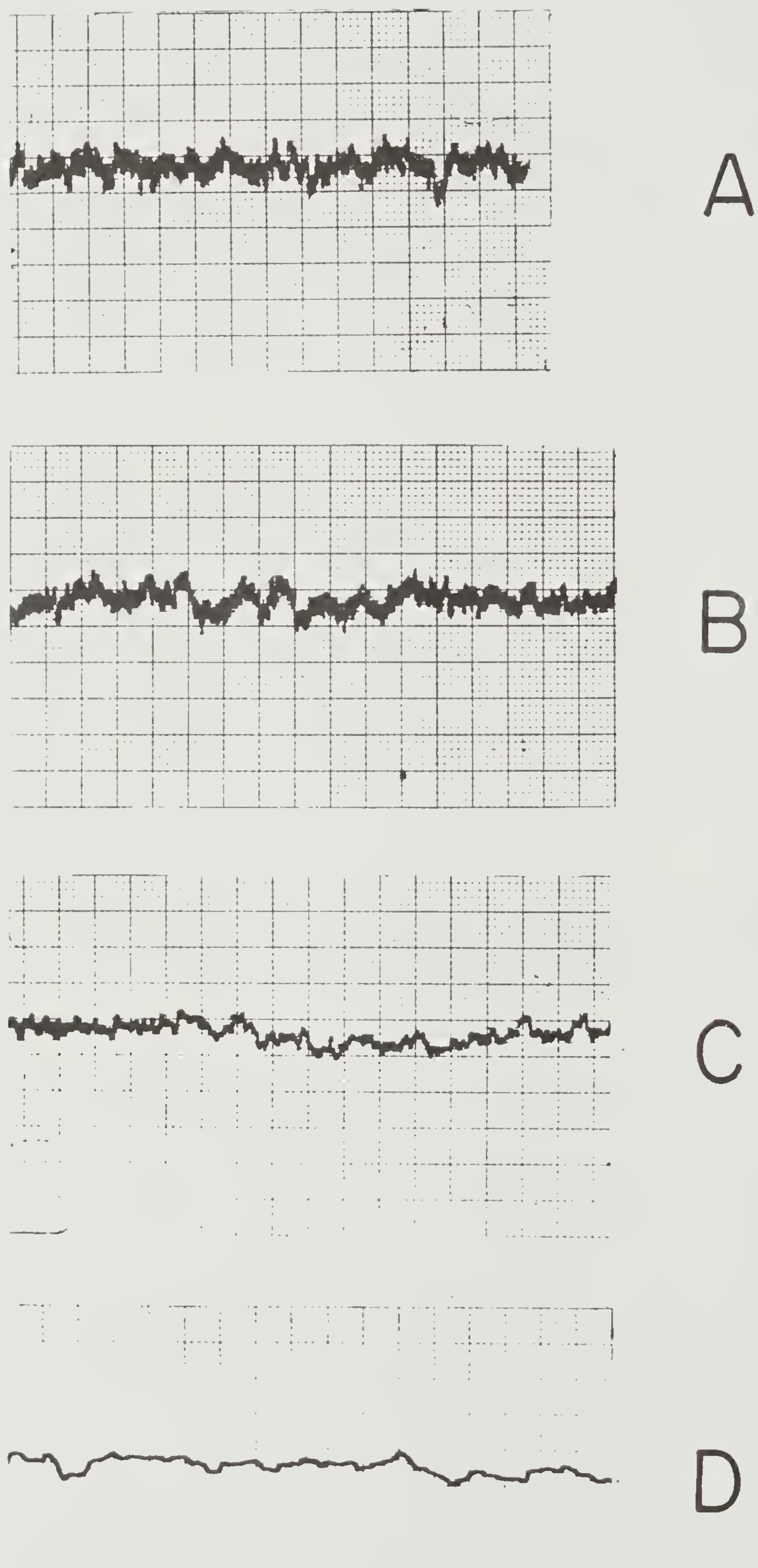


Figure 7.

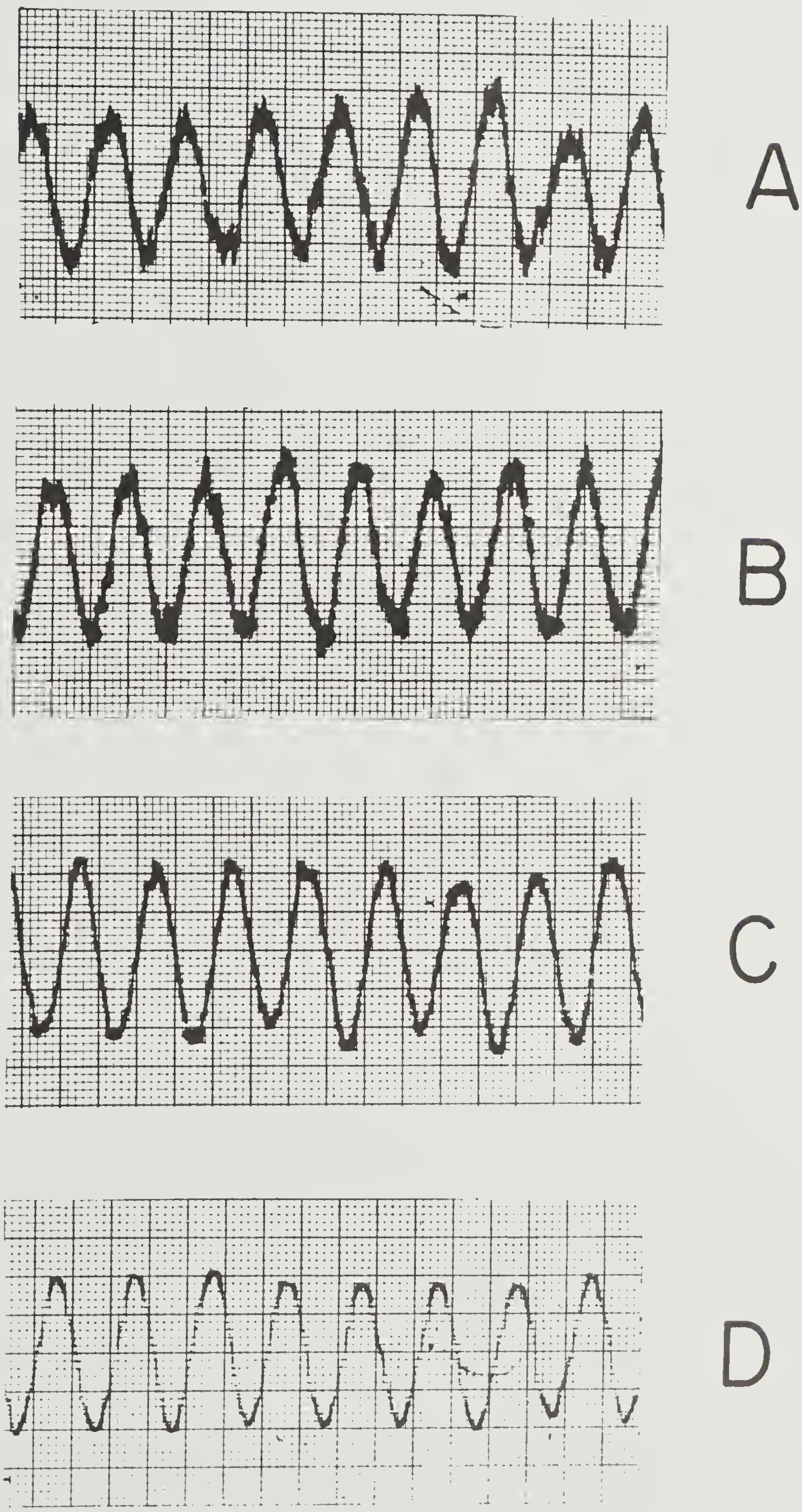


Figure 8.

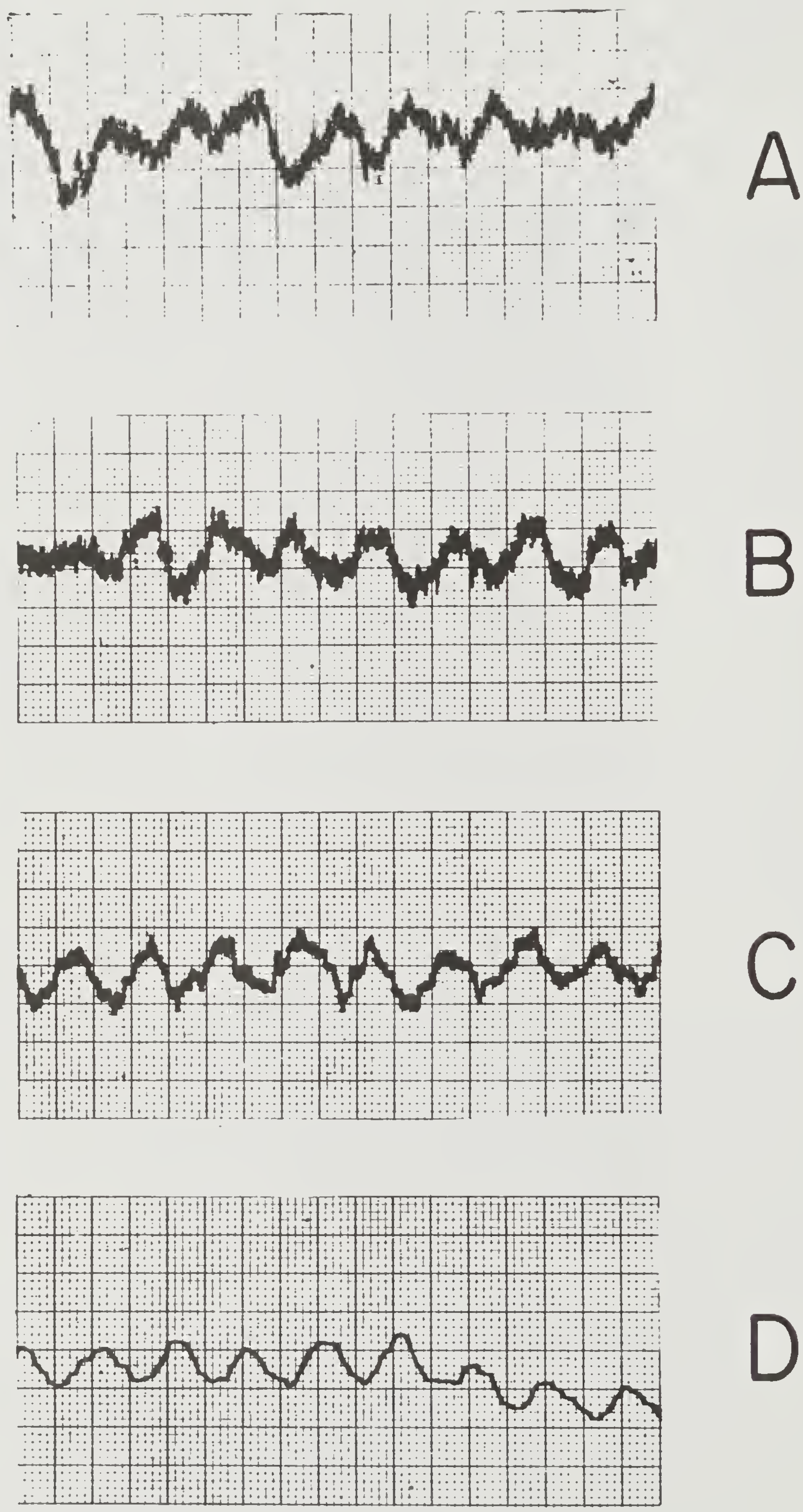
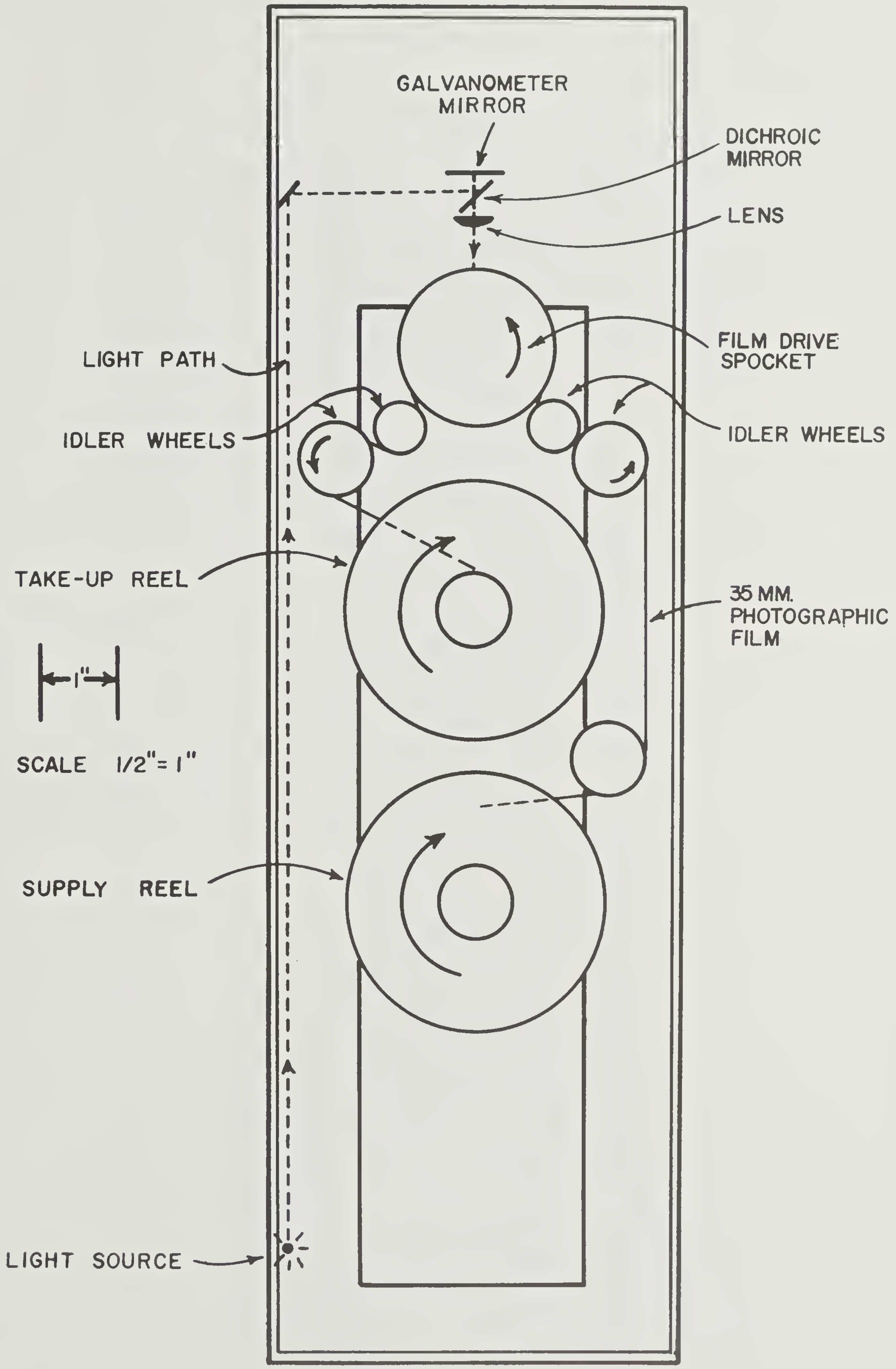


Figure 9.



SCHEMATIC DRAWING OF FILM RECORDER FIG. 10

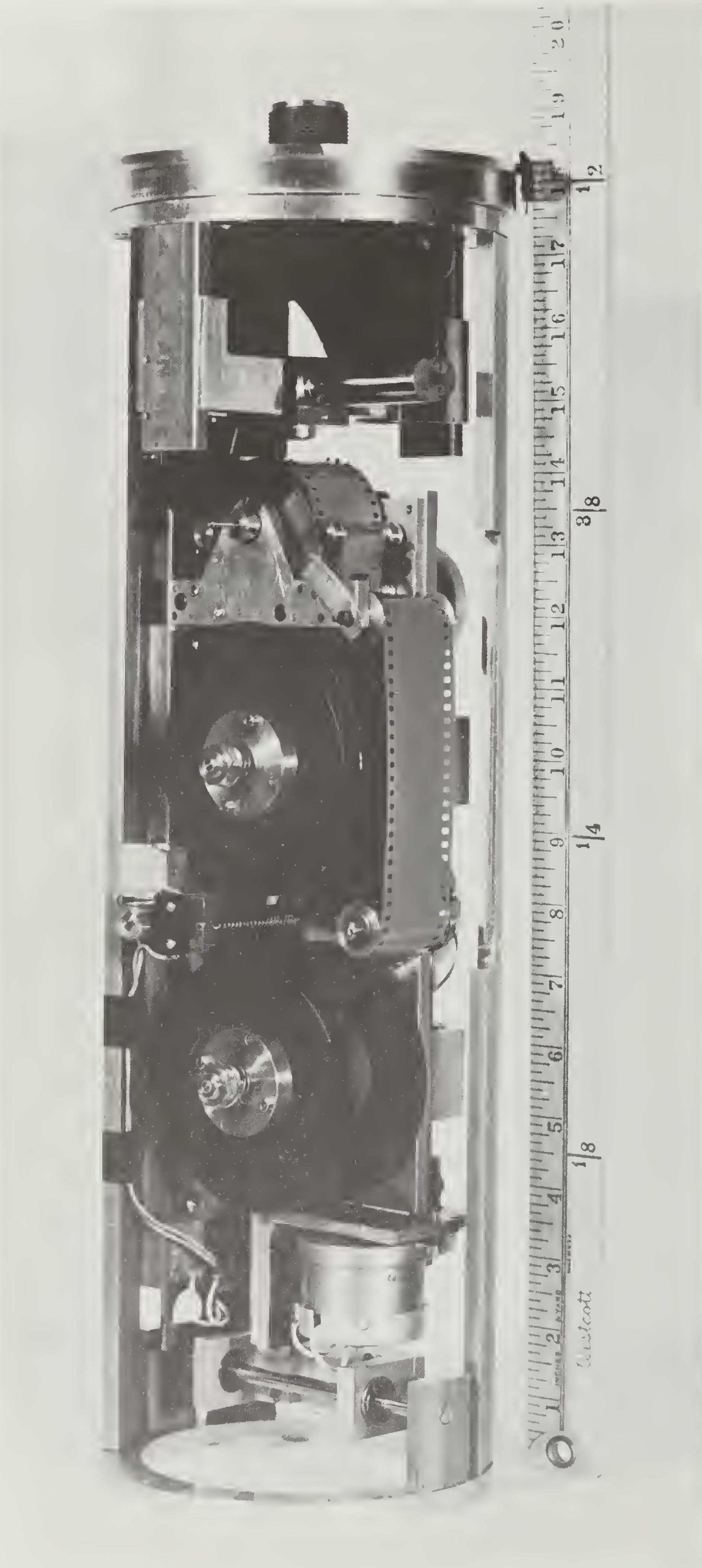
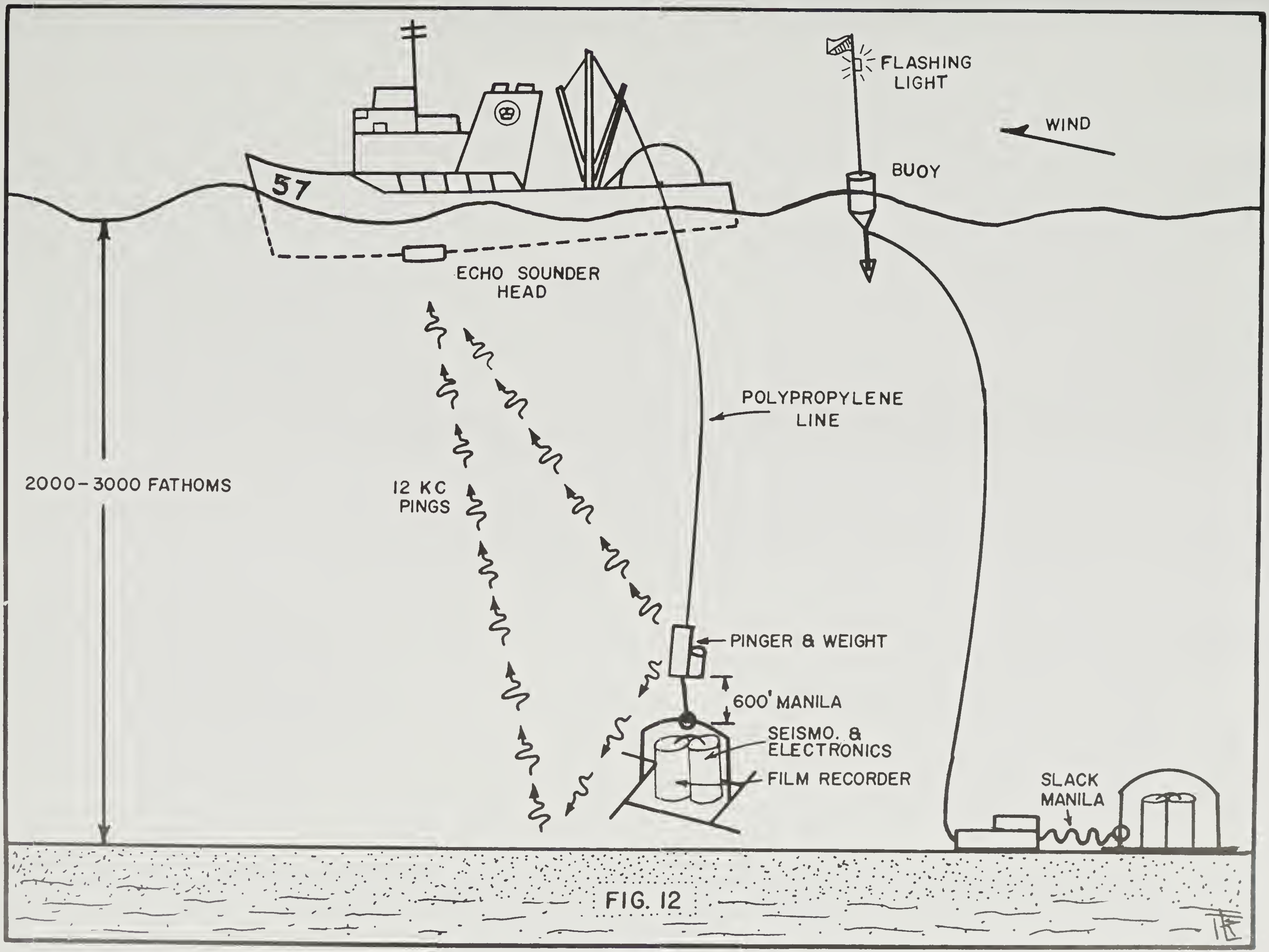


Fig. 11.



FLASHING
LIGHT
WIND
BUOY
57
ECHO SOUNDER
HEAD
POLYPROPYLENE
LINE
2000-3000 FATHOMS
12 KC
PINGS
PINGER & WEIGHT
600' MANILA
SEISMO. &
ELECTRONICS
FILM RECORDER
SLACK
MANILA

FIG. 12